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# OPTICAL FIRE DETECTOR TESTING IN THE AIRCRAFT ENGINE NACELLE FIRE TEST SIMULATOR



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Optical fire detector systems for aircraft engine compartments provided by fire vendors were evaluated in the Aircraft Engine Compartment Fire Test Simulator (AENFTS). Their ability to sense JP-4 fires of two sizes and provide fire warnings in a variety of simulated flight environments was monitored along with their freedom from false fire warnings. One systems was identified which provided fire warnings for every test fire and was completely free of false alarms.

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11. TITLE: Optical Fire Detector Testing in the Aircraft Engine Nacelle Fire Test Simulator

# SUMMARY


Engine compartment optical fire sensors provided by Armtec, Pyrotector, Santa Barbara Research Center and Walter Kidde Company were tested in the Aircraft Engine Nacelle Fire Test Simulator (AENFTS) at WPAFB. Systron Donner and HTL/K West were unable to complete development of their sensors within the time deadline for AENFTS testing. Fenwall chose not to participate in the program.

Considerable optical fire sensor data had been obtained in the AENFTS facility using an HTL/Graviner ultraviolet sensor. This device responded accurately to all test fires but all these fires were relatively large fires. Accordingly, the HTL/Graviner sensor was tested with small fires, for various nacelle altitude and ram pressure simulations and against several false alarm sources. The resulting performance data of the HTL/Graviner sensor were used as baseline sensor performance data.

<u>HTL/Graviner Sensor System</u>

The HTL/Graviner sensor system consisted of a single UV detector cell with a microcomputer and crew warning unit. With the larger (31.2 gallon per hour (GPH)) fires, the sensor system provided a fire warning for every fire. With the smaller (1 gallon per hour (GPH)) fires, the sensor system provided a fire warning for six out of the seven planned test conditions. The exception occurred at the highest nacelle airflow and ram air pressure simulation (2 lbs/sec at 24 psia), a condition projected for advanced aircraft but not encountered on current aircraft.

No false alarms were observed during the hot engine soak tests, the hot engine bleed duct tests or with the aircraft strobe light. However, arc welding caused the detector to indicate the presence of a fire within about one second after the arc was struck.

<u>Pyrotector Sensor System</u>

The Pyrotector AENFTS optical fire sensor system installation consisted of a small cylindrical sensor unit with a single flat lens covering the detectors, a crew warning unit (CWU) box mounted above the AENFTS viewing window, and

connecting cables. The sensor, which was mounted in the same position as the HTL/Graviner sensor, reportedly contained one or more narrow band infrared (IR) sensors and responded to flicker.

The Pyrotector sensor responded to every fire but did not respond to any of the false alarms. No test time was lost due to modification, repair or replacement of the Pyrotector equipment.

Armtec Sensor System

The Armtec optical fire sensor system consisted of a sensor unit containing three detectors, which was mounted in the same position as the HTL/Graviner and Pyrotector units, and a control unit containing a microprocessor that was mounted outside AENFTS test section.

The Armtec sensor system also performed without equipment malfunction during the entire test period. With the 1 GPH fires, the Armtec system provided fire warnings for five of the seven planned test conditions; with the 31.2 GPH fires, it provided a fire warning for every fire. No fire warning resulted during any of the false alarm tests.

Other Sensor Systems

Performance of the optical detector systems provided by Santa Barbara Research Center and the Walter Kidde Company was significantly poorer than that of the Pyrotector and Armtec systems. Descriptions of these systems and detailed discussions of the tests results obtained with them are included in Section 3.0 and 4.0 of this document.

Sensor System Status

The sensor systems tested were in various stages of development and most would require additional development to produce flightweight hardware and pass environmental tests. The HTL/Graviner system employed as a baseline for these tests has been flight qualified and subjected to Mil-Std-810 environmental testing.

## PREFACE

This is a technical operating report of work conducted under F33615-84-C-2431 and submitted by the Boeing Military Airplane Company, Seattle, Washington for the period 30 August 1985 through 10 October 1986. Program sponsorship and guidance were provided by the Fire Protection Branch of the Aero Propulsion Laboratory (AFWAL/POSH), Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, Under Project 3048, Task 07, and Work Unit 94. Robert G. Clodfelter was the program manager. Additional funds for this effort were provided by the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS).

The contents of this report cover a portion of the work defined under Task III of the contract, Aircraft Engine Nacelle Fire Test Simulator (AENFTS) Test Requirements. In general, the task requires utilization of the AENFTS to establish the fire initiation, propagation, and damage effects exhibited by aircraft combustible fluids under representative dynamic operational environmental conditions, followed by the evaluation and development of protection measures. One other report of results has been submitted to date under Task III.

| Boeing Document Number | Title |
|---|---|
| D180-29965-1 | Effects of Aircraft Engine Bleed Air Duct Failures on Surrounding Aircraft Structure (April 1987) |

The test program was performed in conjunction with a similar program being conducted in the F-111 test aircraft at the Federal Aviation Administration's Technical Center (FAA/TC) at Atlantic City, New Jersey. Both programs were initiated to determine whether current optical fire detector systems would provide adequate sensitivity to fires and resistance to false alarms in

aircraft engine compartments. The test program discussed herein emphasized sensor performance whereas the FAA/TC program emphasizes the performance of complete fire detection systems.

The main thrust of the AENFTS testing was to evaluate the response of various sensors to large and small fires at simulated flight conditions and false alarm signals. In the AENFTS the fire sensor location and the location of the fire were predetermined. The testing at the FAA will focus on sensor response to fires in a variety of locations throughout the engine compartment. The sensor manufacturer will not have been advised concerning these locations prior to testing. To protect the F-111 test article, smaller fires and more limited flight simulations will be used, compared with those possible in the AENFTS.

Five optical fire sensors were tested in the AENFTS. Baseline tests were performed on an HTL/Graviner system which is currently being flight tested on an F-111 airplane. Tests were also conducted on sensors provided by Walter Kidde, Santa Barbara Research Center, Armtec and Pyrotector. The Pyrotector sensor was the only sensor that responded to all the AENFTS fire tests and to none of the simulated false alarms. All vendors agreed to public release of the test results.

Boeing wishes to acknowledge with appreciation the contributions of the following to this program: Lt. Maria D. Rodriguez, the Air Force Project Engineer, who provided overall program direction, Robert E. Esch of SelectTech Services Corp. of Dayton, the test technician, Albert J. Meyer, SelectTech, the test instrumentation engineer and Tracey L. Ledwick, also of SelectTech, the programmer and computer operator. Contributions from the various fire detector vendors were particularly important and included help with the planning of the

program, provision of the systems for evaluation and their installation and operation. Contributors included:

Walter Kidde Company
Anthony Scofield, Gordon Nelson, Dr. Edward Manring, Robert Glaser and Mark Mitchell

SBRC
Mark Kern, Dan Snider and Ken Shamordola

Armtec
John Jordan and Art Pearson

HTL
Tom Hillman and Mike Cullen

Pyrotector
Robert Dunbar and David Estrela

Key Boeing contributors to the program were: Alan M. Johnson, test supervision, and Lynn Desmarais, report preparation assistance.

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# 1.0 INTRODUCTION

The suitability of currently available optical fire sensors for use in aircraft engine compartments was investigated in the Aircraft Engine Nacelle Fire Test Simulator (AENFTS) at Wright Patterson Air Force Base (WPAFB). Sensors provided by four vendors were evaluated and compared with a baseline ultraviolet (UV) aircraft engine compartment fire sensor that had been used extensively in previous AENFTS testing. The sensitivity of the sensors to JP-4 fires of several sizes at various simulated flight conditions was investigated along with their immunity to a variety of simulated false alarms.

## 1.1 Background

Most current Air Force aircraft have continuous loop fire detection systems installed in their engine compartments to detect engine fires and/or overheat conditions. Three major problems with this type of protection have been experienced during the last several decades:

- o These systems are prone to damage during maintenance work, particularly during removal and replacement of engines.
- o A small fire or a fire sufficiently far from the detector will not be detected.
- o The relatively high false alarm rate has eroded crew confidence in these systems.

During the late 1970's General Dynamics developed a prototype ultraviolet (UV) fire sensor system under contract F33614-77-C-2029, with help from HTL Industries Incorporated and Graviner LTD. This system was installed on an F-111 test airplane for evaluation as part of that contract. Tests on the UV system indicated that its immunity to false alarms was significantly better than the continuous element systems. Once the UV system was installed on the airplane, however, its sensitivity to fires in that environment was never demonstrated.

Following completion of the work under that contract, one of the two available prototype systems remained on the flight test F-111 for further evaluation and the other was moved to WPAFB where it became available for evaluation in the

AENFTS. A single detector head was installed in the F-16 Nacelle Simulator in the AENFTS. The sensor's performance was observed over the the next two years as several hundred fires were ignited and extinguished as part of agent evaluation testing in the AENFTS (Ref. 1). The system's sensitivity to the AENFTS test fires was excellent.

In July of 1985, representatives of all U.S. aircraft fire sensor system manufacturers were invited to a meeting at the Federal Aviation Administration's Technical Center (FAA/TC) at Atlantic City, New Jersey. The purpose of this meeting was to identify promising new technology sensors and to conduct tests to compare the performance of these sensors.

Included in this meeting were representatives from:

Armtec Industries, Incorporated
Fenwal Incorporated Division of Kidde, Incorporated
HTL K West/Systems Division of HTL Industries, Incorporated
Santa Barbara Research Center of the Hughes Aircraft Company
Systron Donner
Walter Kidde Division of Kidde, Incorporated

A test program was developed that involved fire tests in the AENFTS and in the FAA/TC's F-111 test article. All the representatives indicated a desire to participate, either during this meeting or subsequently. Later, contact was also made with Pyrotector, Incorporated. The test program was described to them and they also indicated a desire to participate. This document describes the test program and results obtained during AENFTS testing at WPAFB between January 1986 and October 1986.

Incidental to progress in the subject test program, an opportunity arose to investigate the HTL/Graviner UV system's long term reliability and false alarm immunity. Representatives from WPAFB's Fire Protection Branch, the USAF Safety Center at Norton AFB, the F-111 and A-10 Program Offices, Boeing and HTL/Graviner met at McClellan AFB in October of 1986 to review the long-term performance of that system accumulated during the five years that it had been installed on a flight test F-111 since work under contract F33614-77-C-2029 was

completed in 1981. Unfortunately, few records concerning the system's performance had been kept during this period and the system did not appear to be functional at the time of that meeting. Representatives from HTL/Graviner investigated the current status of the system thoroughly and prepared a report that is included in this document as Appendix A.

## 1.2 Objectives and Approach

Specific objectives of the AENFTS testing were to investigate the sensor's:

- o Sensitivity to large and small fires in a simulated engine compartment
- o Performance at simulated altitude and ram pressure conditions
- o Immunity to simulated false alarms
- o Response to high temperature airflow

The overall objective was to identify sensors that showed promise as the foundation for advanced engine compartment fire detection systems.

To achieve these objectives the sensors were exposed to:

- o Small fires (1 gallon per hour of JP-4 fuel) and large fires (31.2 gallons per hour of JP-4 fuel) in the AENFTS facility.
- o Simulated engine compartment altitudes and ram air pressures representative of conditions in current and advanced aircraft.
- o Several false alarm radiation signals
- o Engine compartment airflow temperatures approaching 300$^{o}$F.

During the earlier AENFTS testing of the HTL/Graviner system, a single optical detector was installed in the AENFTS's F-16 nacelle simulator and a Crew Warning Unit (CWU) was installed above the main AENFTS viewing window so that the fire warning light could be observed in the control room and its response to the fire

recorded on video tape. With the above objectives in mind, it was decided the detector and CWU units and for the sensors to be evaluated would be installed in the same position as had been employed for the HTL/Graviner sensor. False alarm tests would be conducted with the sensors moved outside the AENFTS test section to allow the false alarm signal sources to be easily operated and moved with respect to the sensors.

During the period between the initial July 1985 meeting and the conduct of the individual tests, the vendors were allowed brief test periods in the AENFTS where they could set up sensors, spectral analysis equipment or combinations of these and observe some of the tests. They were also provided with copies of video tapes showing these test fires viewed through the main AENFTS viewing window.

## 2.0 TEST FACILITIES

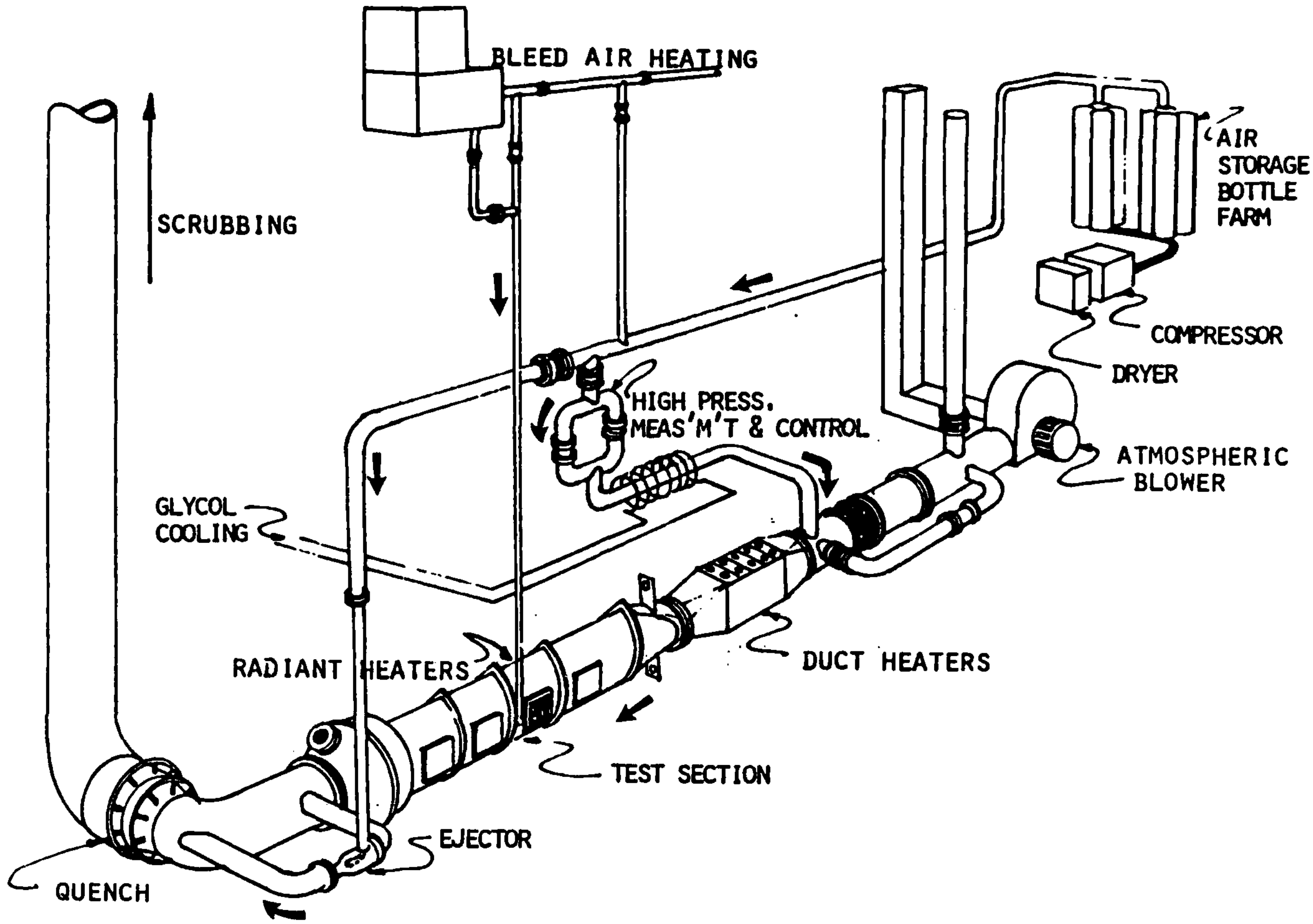
### 2.1 AENFTS Facility

The Aircraft Engine Nacelle Fire Test Simulator (AENFTS) is a ground test facility designed to simulate potential fire hazards in the annular compartment around an aircraft engine. The facility is installed in I-Bay of Building 71-B in Area B of Wright-Patterson Air Force Base, Ohio. The facility includes air delivery and conditioning equipment designed to simulate engine compartment ventilation and bleed airflow, a test section within which fire testing can safely be conducted and an exhaust system which can cool the combustion products and scrub them sufficiently to allow their release into the atmosphere (Figure 1).

The test section of the AENFTS (Figure 2) consists of a two radian (114 degree) segment of the annulus between a 15 inch radius duct, which simulated an engine case, and a 24 inch radius duct, which simulated the engine compartment outer wall. It is approximately 14 feet long and is constructed from 1/4 inch stainless steel. Various access ports and viewing windows are provided for access to test equipment and instrumentation and for observation of the test activities taking place within.

Aircraft engine compartment ventilation air velocity, pressure and temperature, fan case temperature, nacelle geometry, and the introduction of aircraft flammable fluids can be simulated. Aircraft fire extinguishing agent release systems can be simulated using various extinguishants, and the effect of these on fires in the AENFTS can be observed and recorded.

As shown in Figure 1, the AENFTS ventilation airflow conditioning systems include a blower which provides air at atmospheric pressure to simulate low speed sea level flight conditions, a high pressure compressor and air storage bottle farm which can provide ventilation airflow simulating ram pressure in low altitude supersonic flight conditions and an air driven ejector which can evacuate the test section to simulate high altitude flight conditions. The shorter curved test section wall, which simulates the case of a turbojet or turbofan engine, can be heated with radiant heaters. The test section can be rotated 360 degrees allowing simulation of any 114 degree segment of an aircraft engine compartment.




(ARROWS INDICATE AIRFLOW DIRECTION)

*Figure 1. Components of the AENFTS*

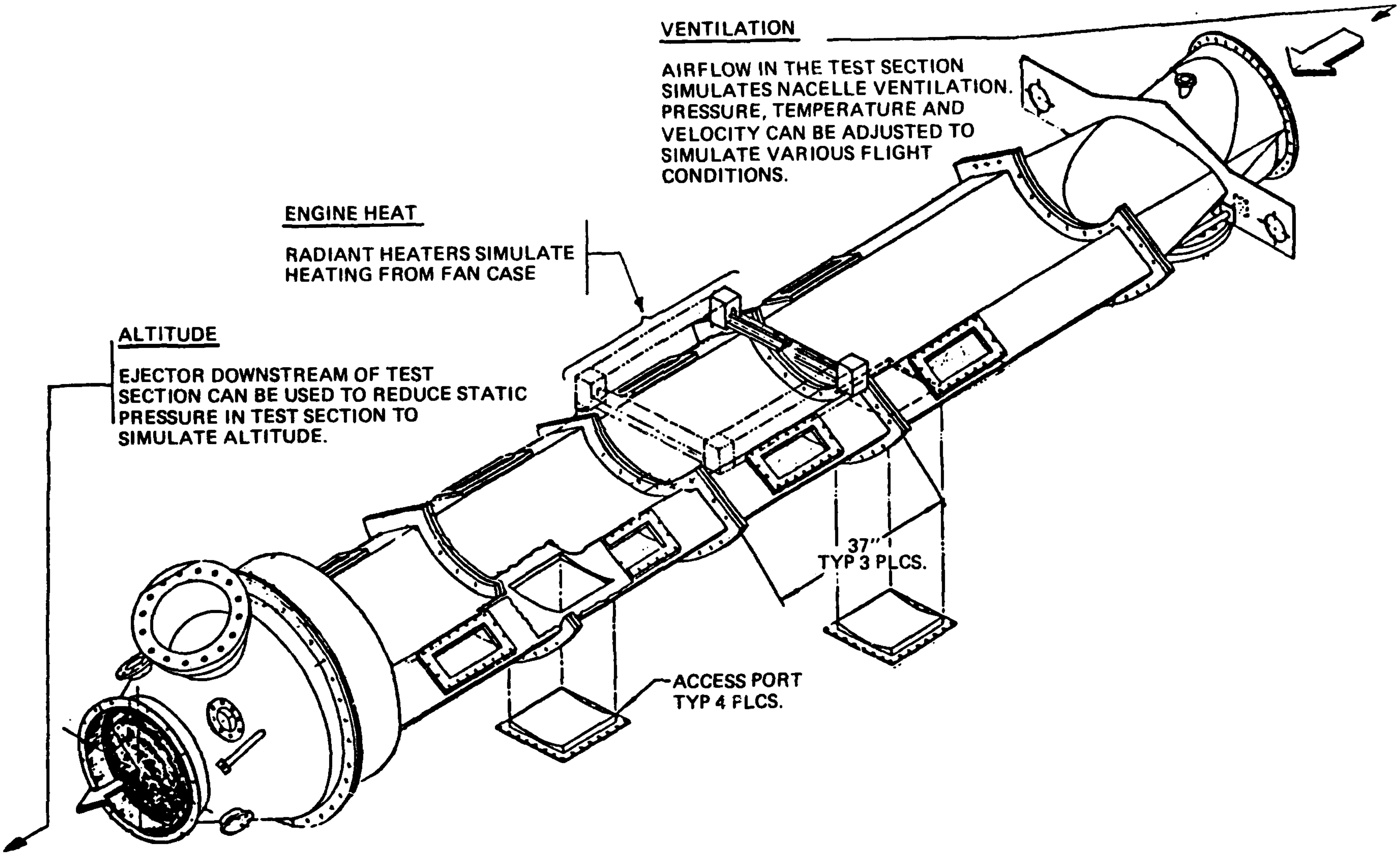



*Figure . 2. AENFTS Test Section*

Additional information concerning the AENFTS is available in Reference 2, the AENFTS Operating Manual.

## 2.2 F-16 Nacelle Simulator, Igniter and Flame Holder

In an actual aircraft engine compartment, the ventilation airflow does not move uniformly as in the clean AENFTS test section. Regions of reverse flow and flow stagnation have been seen in the F-111 being tested by the Federal Aviation Administration's Technical Center (FAA/TC) and the F-111 engine compartment is cleaner and designed for higher ventilation airflow rates than the F-15 and F-16 engine compartments. To simulate a more realistic environment, having the complex of tubes, ribs, clamps, wires, and other flow disturbances of a real aircraft engine compartment, a region of the F-16 nacelle was simulated for testing in the AENFTS during 1984.

The forward right side of the F-100 engine as it is installed in the F-16 is shown in Figure 3. An early prototype F-100 engine was obtained and the components in this region were removed and installed on a 5 foot long simulated engine side stainless steel base plate constructed to fit the engine side of the AENFTS test section (Figure 4). Intrusion into this region of the glove tank and structural ribs was simulated in sheet metal and fitted into the AENFTS test section over the engine side base plate. The remaining AENFTS test section length, approximately 60 inches, simulated the less cluttered annulus around the afterburner.

To further simulate the F-16 installation, the AENFTS test section was rotated to the seven o'clock to eleven o'clock position (looking aft). A fused quartz viewing window was provided in the 15 inch square access port on the nacelle side of the AENFTS which opened onto the forward "arch" of the F-16 bleed duct which was the planned fire zone.

In the F-16, ventilation air enters the engine compartment through a scoop inlet on each side adjacent to the fan face of the engine and in some operating conditions, through spring loaded fire doors near the base of the engine compartment, about 18 inches aft of the scoops. These were simulated with an inlet baffle plate at the fan face location with slotted openings approximating one third of the area of the aircraft nacelle ventilation inlets and fire doors.

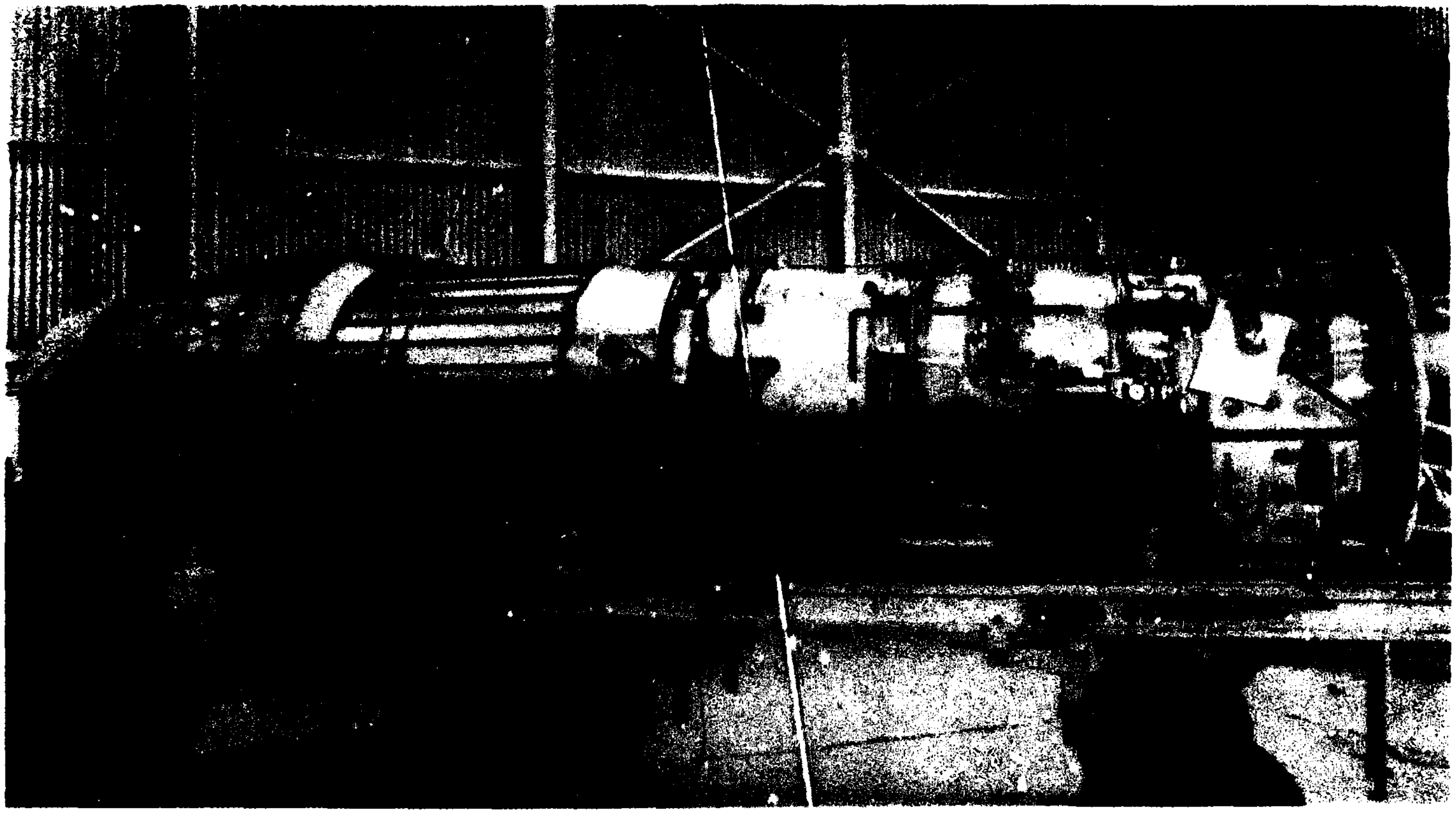


*Figure 3. F—100 Engine Showing Accessories for F—16 Simulator*

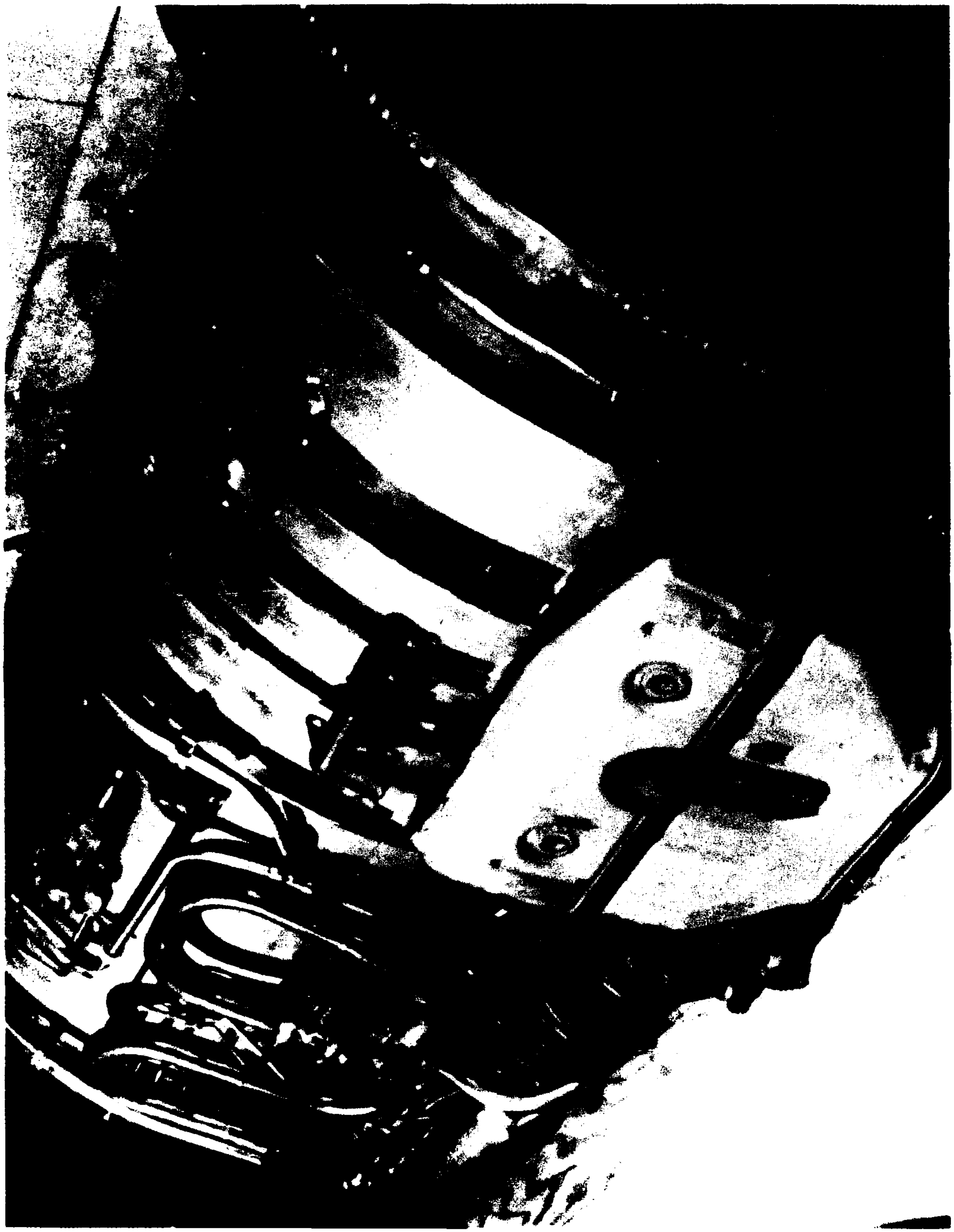


*Figure 4. F-16 Simulator Engine Side*

A baffle plate was also placed at the exit end of the last AENFTS test section to simulate the flow area in the F-16 engine compartment as the ventilation flow exits around the afterburner.

A fuel injection nozzle is located in the shelter of the simulated aircraft rib structure adjacent to the leading edge of the viewing window. A "vee-channel" flameholder is installed around the fuel nozzle. Two spray nozzles were employed to inject JP-4 into the simulator for all optical fire sensor tests. These included a 1.0 GPH oil burner nozzle, a duplicate of the nozzle to be employed during the optical detector testing at FAA/TC and a 31.2 GPH stainless steel hollow core 80 degree atomizing spray nozzle.

Earlier AENFTS testing with the HTL/Graviner detector was complicated by the UV sensor's response to a spark igniter that was installed adjacent to the flameholder. A propane fueled igniter was developed which allowed the spark to be relocated outside of the test section, eliminating this problem.

## 2.3 Instrumentation, Data Acquisition and Data Reduction

### 2.3.1 Basic Test Instrumentation

The basic test instrumentation (Figure 5) consisted of the sensors employed to measure the simulated engine compartment ventilation air temperature, pressure and flowrate, whether it was supplied by the atmospheric blower or by one of the high pressure air systems, and the temperatures in the test section. Additional equipment was employed to acquire video records of the testing.

Seventeen pressure transducers were used to acquire pressure data during these tests. These transducers were standard commercial products manufactured by Sensotec and Setra. They were precalibrated by their manufacturers with standards traceable to the National Bureau of Standards. Their calibration had been periodically checked during the last several years using a dead weight tester. Details of the transducer ranges, sensitivities and accuracies are included in Table 1.

Type J, K and T thermocouples were used to measure the simulated ventilation airflow temperature at the flowmeters, the air temperature in the test section

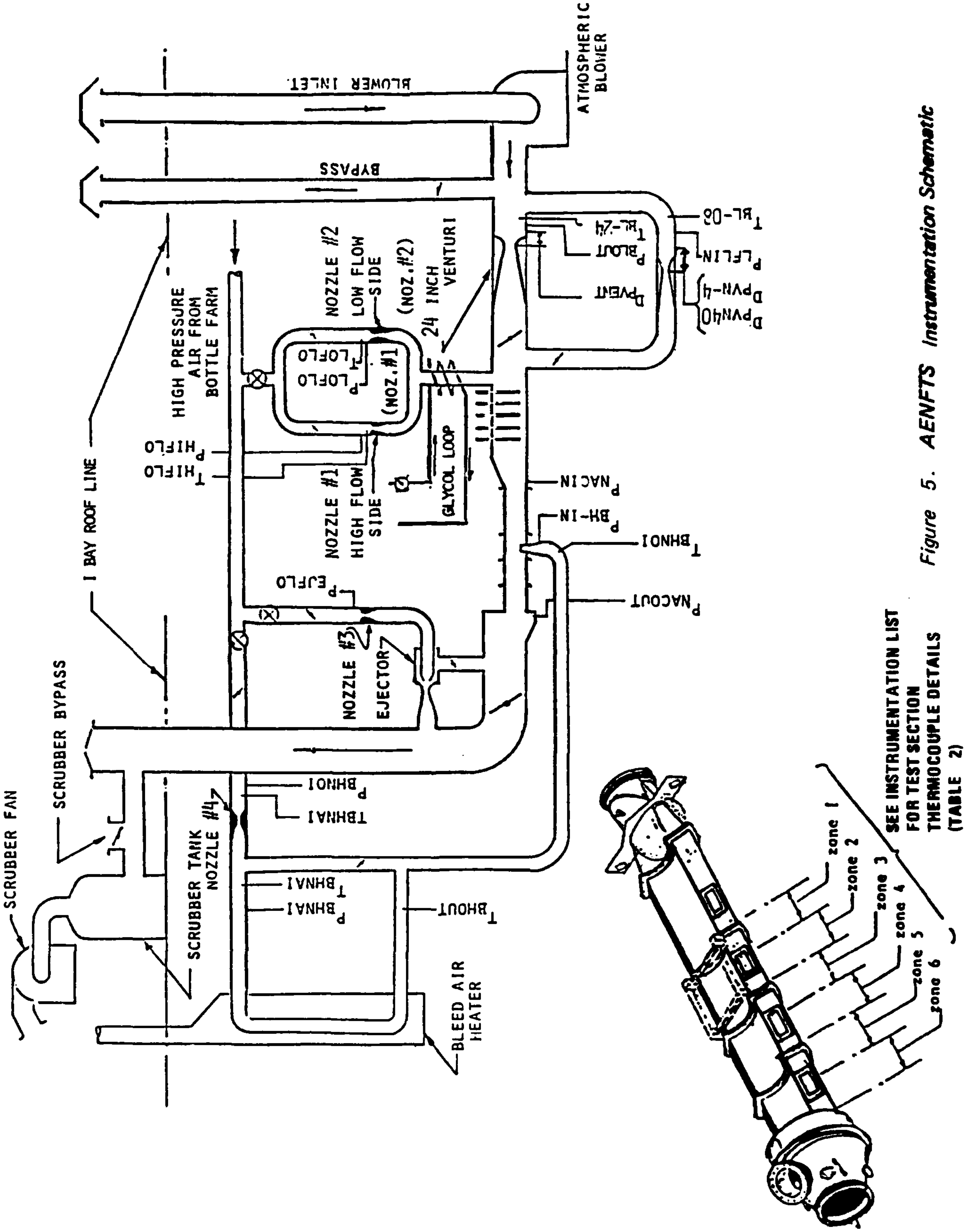



*Figure 5. **AENFTS** Instrumentation Schematic*

*Table 1. Details of AENFTS Pressure Measurement*

| PRESSURE NUMBER | MODCOMP CHANNEL | SOFTWARE SYMBOL | ITEM DESCRIPTION | MFG&S/N | RANGE | ACCURACY |
|---|---|---|---|---|---|---|
| PT-1 | 57 | PBLOUT | Blower outlet press | S-34212 | 0-50 in. H20 | +0.25 |
| PT-2 | 69 | DPVENT | 24" venturi delta P | S-33659 | 0-60 in. H2O | +0.5 |
| PT-4 | 59 | PNACIN | AEN inlet press | S-34214 | 0-30 psia | +0.25 |
| PT-5 | 60 | PEXFAN | Scrubber inlet press | S-27984 | 0-16 in. H2O | +0.25 |
| PT-6 | 61 | PHIFLO | Hi press/hi flow nozzle press | | 0-1000 psia | +0.25 |
| PT-7 | 62 | PLOFLO | Hi press/lo flow nozzle press | | 0-640 psia | +0.25 |
| PT-8 | 63 | PEJFLO | Ejector nozzle press | | 0-500 psia | +0.25 |
| PT-9 | 64 | PNCOUT | AEN outlet press | | 0-30 psig | +0.25 |
| PT-10 | 65 | P-STOR | High press line press | | 0-2500 psig | +0.25 |
| PT-11 | 66 | P-FUEL | Fuel reservoir press | S-34218 | 0-420 psig | +0.5 |
| PT-12 | 67 | P--HYD | Hydraulic reservoir | | 0-5000 psig | +0.25 |
| PT-13 | 68 | PBAROM | Barometric press | S-40737 | 26-32 in.Hg | +0.25 |
| PT-14 | 78 | PNZFUL | Fuel nozzle press | S-48291 | 0-500 psig | +0.25 |
| PT-15 | 77 | PNZHYD | Hydraulic fluid nozzle press | | 0-5000 psig | +0.25 |
| PT-16 | 79 | PLFLIN | 8" venturi inlet press | S-50823 | +1.5 psig | +0.1 |
| PT-17 | 51 | DPVN-4 | 8" venturi delta P | M-21784-1 | 0-4 in. H2O | +0.15 |
| PT-18 | 50 | DPVN40 | 8" venturi delta P | M-21784-2 | 0-40 in. H2O | +0.15 |

Manufacturers: S: Sensotec
M: MKS
ST: Setra

*Percent of full scale reading

and surface temperatures along the AENFTS and the F-16 nacelle simulator. Table 2 describes the location, nomenclature, channel assignment, accuracy and measurement location of all these thermocouples.

### 2.3.2 AENFTS Video Instrumentation

A closed circuit television camera equipped with a F 2.8, 15- to 150-mm zoom lens was mounted on a pan and tilt platform. During these tests, the camera was focused on the main AENFTS viewing window so that both the test fires and the sensor system's CWU were observed. The output signal could be monitored on a video monitor on the AENFTS control panel to allow the test operator to observe the test fire and the sensor system's response.

A date/time generator provided date and time information (to the nearest second) which was also displayed at the top of the screen on the control room video monitor. A U-matic format video tape recorder also received signals from the video camera in the test cell and from the date/time generator. Video tapes were made of all the optical fire detector tests using this equipment. Because 60 video fields were acquired per second, the actual timing resolution available replaying the tapes was about 1/60-th second.

### 2.3.3 Acquisition and Reduction of Basic AENFTS Data

The AENFTS facility computer is a 16-bit, general purpose, digital computer for real time multi-programming applications with 64 K RAM memory manufactured by Modular Computer Systems Inc. (ModComp) of Ft. Lauderdale, Florida.

Data was acquired by the AENFTS computer and reduced to appropriate pressure and temperature engineering units using previously acquired calibration data. Once the ModComp computer had calculated engineering unit data for the thermocouples and pressure transducers and the bleed air system flow meter, these data were displayed on the control console monitor and output to the line printer and ModComp data disk for storage. The actual data reduction equations employed are included in Appendix B of this report. Further details concerning the ModComp computer and the software employed are available (References 3 and 4).

A video tape record was made of all tests to allow re-examination of test events after their occurrence, determination system response times and allow direct comparison of tests run at different times.

*Table 2. Details of AENFTS Temperature Measurement*

| THERMO-COUPLE NUMBER | MODCOMP CHANNEL | SOFTWARE SYMBOL | DESCRIPTION | TYPE | ACCURACY |
|---|---|---|---|---|---|
| TC-28 | 1 | TENG1A | Engine side skin temp zone 1 | K | ±4 degrees F. |
| TC-29 | 2 | TENG1B | Engine side skin temp zone 1 | | |
| TC-30 | 3 | TENG2A | Engine side skin temp zone 2 | | |
| TC-31 | 4 | TENG2B | Engine side skin temp zone 2 | | |
| TC-32 | 5 | TENG3A | Engine side skin temp zone 3 | | |
| TC-33 | 6 | TENG3B | Engine side skin temp zone 3 | | |
| TC-34 | 7 | TENG4A | Engine side skin temp zone 4 | | |
| TC-35 | 8 | TENG4B | Engine side skin temp zone 4 | | |
| TC-36 | 9 | TENG5A | Engine side skin temp zone 5 | | |
| TC-37 | 10 | TENG5B | Engine side skin temp zone 5 | | |
| TC-38 | 11 | TENG6A | Engine side skin temp zone 6 | | |
| TC-39 | 12 | TENG6B | Engine side skin temp zone 6 | | |
| TC-40 | 13 | TAIR-1 | Nacelle air temp zone 1 | | |
| TC-41 | 14 | TAIR-2 | Nacelle air temp zone 2 | | |
| TC-42 | 15 | TAIR-3 | Nacelle air temp zone 3 | | |
| TC-43 | 16 | TAIR-4 | Nacelle air temp zone 4 | | |
| TC-44 | 17 | TAIR-5 | Nacelle air temp zone 5 | | |
| TC-45 | 18 | TAIR-6 | Nacelle air temp zone 6 | | |
| TC-46 | 19 | TNAC1A | Nacelle side skin temp zone 1 | | |
| TC-47 | 20 | TNAC1B | Nacelle side skin temp zone 1 | | |
| TC-48 | 21 | TNAC2A | Nacelle side skin temp zone 2 | | |
| TC-49 | 22 | TNAC2B | Nacelle side skin temp zone 2 | | |
| TC-50 | 23 | TNAC3A | Nacelle side skin temp zone 3 | | |
| TC-51 | 24 | TNAC3B | Nacelle side skin temp zone 3 | | |
| TC-52 | 105 | TF16-1 | Test article temp #1 | | |
| TC-53 | 106 | TF16-2 | Test article temp #2 | | |
| TC-54 | 107 | TF16-3 | Test article temp #3 | | |
| TC-55 | 108 | TF16-4 | Test article temp #4 | | |
| TC-56 | 109 | TF16-5 | Test article temp #5 | | |
| TC-57 | 110 | TF16-6 | Test article temp #6 | | |
| TC-58 | 111 | TF16-7 | Test article temp #7 | | |
| TC-58 | 31 | TOUTLG | Nacelle outlet air temp (long) | | |
| TC-59 | 32 | TOUTSH | Nacelle outlet air temp (short) | | |
| TC-60 | 33 | TNACIN | Nacelle inlet air temp | K | |
| TC-61 | 34 | TBL-08 | Low flow venturi temp | T | |
| TC-62 | 35 | TBL-24 | Blower outlet temp | K | |
| TC-63 | 35 | T-NIFL | Hi flo/Hi press temp | | |
| TC-64 | 37 | TSTKLO | Lower exhaust stack temp | | |
| TC-65 | 38 | TSTKUP | Upper exhaust stack temp | | |
| TC-70 | 39 | OATPAD | Pad outside air temp | | |
| | 40 | OAT-RF | Roof outside air temp | | |
| | 41 | TNACRM | Nacelle room air temp | | |
| | 43 | T-NPAD | North pad temp | K | |
| | 44 | RTDREF | Reference room temp | T | |
| TC-72 | 45 | TGLYCO | Cold glycol temp | J | |
| TC-74 | 47 | T--HYD | Hyd. reservoir temp | J | |
| TC-75 | 46 | T-FUEL | Fuel injection reservoir temp | J | |
| TC-91 | 94 | TLOFLO | Lo-flo/Hi-press temp | T | ±4 degrees F. |

2.3.4 Disposition of Test Data

All test data, including run logs, magnetic tapes of ModComp data, "floppy" disks containing Lotus 1-2-3 worksheets and plot files and video tapes acquired during testing are on file in the BMAC test office in I-Bay of Bldg. 71B at Wright-Patterson Air Force Base.

2.4 Test Procedure

The optical fire sensors were exposed to a variety of one gallon per hour (GPH) and 31.2 GPH JP-4 fuel fires at various airflows ranging from 0.5 to 6 lbs/second, using the atmospheric blower, high pressure air supply and ejector systems to simulate various flight conditions. Several false alarm tests were also conducted, employing heat, light and electrical arc radiation sources.

2.4.1 Sensitivity Tests

Each of the optical fire detector systems was exposed to the same series of JP-4 test fires in the AENFTS. Table 3 identifies the fire size and ventilation air flow conditions employed. These tests were generally run in the following manner:

1. Ventilation airflow conditions were established and allowed to stabilize until the desired flowrate and temperature were displayed on the control console monitor. The fuel reservoir pressure was adjusted to 175 psig.

2. Tabular data were acquired using the Modcomp computer.

3. The Video tape recorder was started.

4. The fire was started with the igniter immediately after initiating fuel flow.

5. The test operator observed the detector system's response to the fire on the control console video monitor.

*Table 3. Sensitivity Test Conditions*

| TEST NO. | VENTILATION AIRFLOW (lb/sec) | TEST SECTION PRESS (psia) | TEST SECTION TEMP. (deg F) | JP-4 FLOWRATE (GPH) |
|---|---|---|---|---|
| 1 | 1.00 | AMB | 100 | 1.0 |
| 2 | 2.50 | AMB | 100 | 1.0 |
| 3 | 0.50 | AMB | 100 | 1.0 |
| 4 | 0.50 | 7.0 | 100 | 1.0 |
| 5 | 1.00 | 10.0 | 100 | 1.0 |
| 6 | 1.00 | 20.0 | 100 | 1.0 |
| 7 | 2.00 | 24.0 | 100 | 1.0 |
| 8 | 1.00 | AMB | 300 | 1.0 |
| 9 | 1.00 | AMB | 100 | 31.2 |
| 10 | 3.50 | AMB | 100 | 31.2 |
| 11 | 6.00 | AMB | 100 | 31.2 |
| 12 | 0.50 | 7.0 | 100 | 31.2 |
| 13 | 1.00 | 10.0 | 100 | 31.2 |
| 14 | 2.00 | 24.0 | 100 | 31.2 |
| 15 | 6.00 | 24.0 | 100 | 31.2 |
| 16 | 1.00 | AMB | 300 | 31.2 |

6. After about ten seconds of burning, the fuel flow was terminated.

7. The video tape recorder was stopped.

8. A cool off period of about five minutes using the atmospheric blower at a flowrate of about seven lbs/second was begun during which manual notes were recorded and the AENFTS switchbox was updated to the next test condition number.

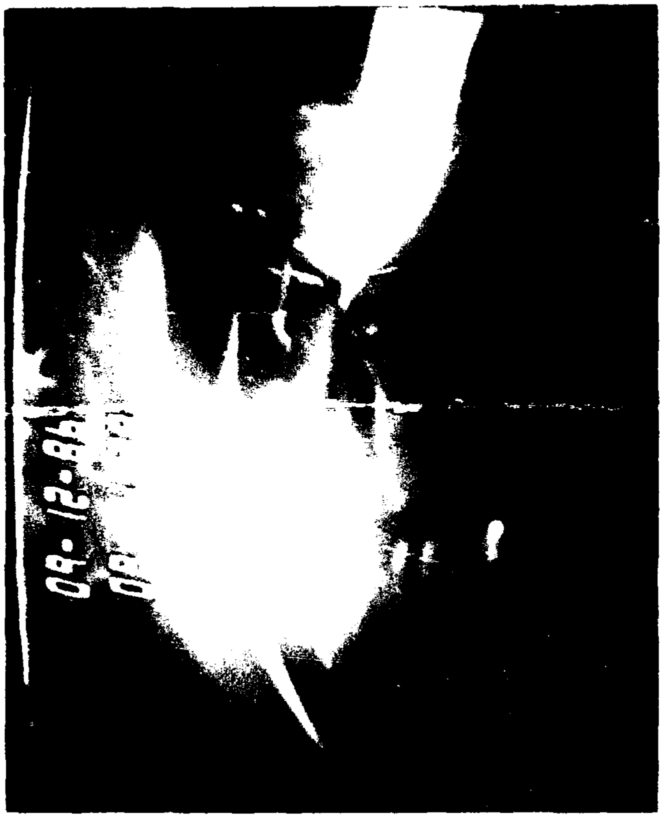
9. When AENFTS side skin and F-16 simulator temperatures had fallen to a maximum of 150°F, the procedure was repeated for the next test condition.

A black and white video camera was installed inside the AENFTS test section, fastened to the forward bulkhead in place of the optical detector sensor units, so that it could be used to view the test fires from the same position as the sensor units. Atmospheric blower tests were repeated so that video tape records could be made of these tests. Photographs were made from single frames of the tapes, and show the sensor's view of the six atmospheric tests (Figures 6 and 7). The camera was equipped with an automatic iris control which adjusted to the available light. Hence, no conclusion should be drawn from Figures 6 and 7 regarding relative brightness of the test fires. The figures do demonstrate that these were a line-of-sight view of some part of the fire in all tests.

### 2.4.2 False Alarm Tests

Each of the optical fire sensors was also exposed to the same series of simulated false alarm situations. These tests were generally run in the following manner:

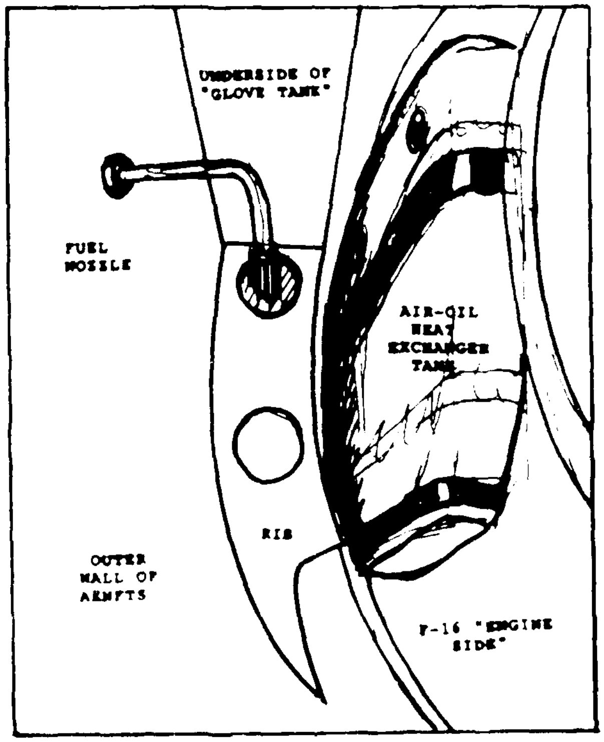
1. Simulated Hot Engine Soak: With detector unit installed in the same position as for the sensitivity tests, a 31.2 GPH JP-4 fire was maintained for 20 seconds with 3.5 pounds per second of ventilation airflow, raising the temperature measured by the engine side thermocouples (TF16-A, B & C) to about 350°F. The fuel was then shut off, extinguishing the fire. The ventilation airflow was then decreased to one lb/sec. The fire was not re-ignited and the CWU was observed to see whether a false alarm fire warning was displayed.



a) 1 lb/sec

c) 6 lbs/sec

b) 3.5 lbs/sec



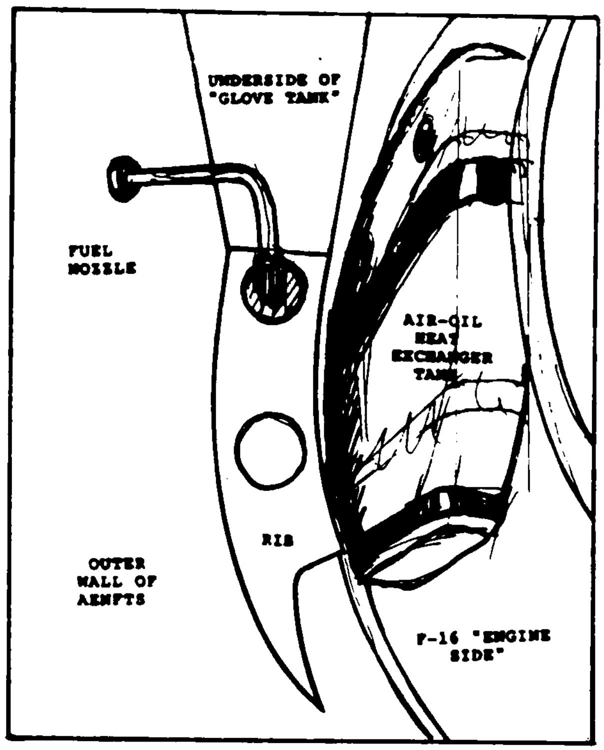

THUMBNAIL DRAWING OF
AREA OF F-16 SIMULATOR
VIEWED BY VIDEO CAMERA

Figure 6   31.2 GPH Fires at Three Ventilation Flowrates

a) 0.5 lbs/sec

c) 2.5 lbs/sec

b) 1.0 lbs/sec




**THUMBNAIL DRAWING OF AREA OF F-16 SIMULATOR VIEWED BY VIDEO CAMERA**

*Figure 7. 1.0 GPH Fires at Three Ventilation Flowrates*

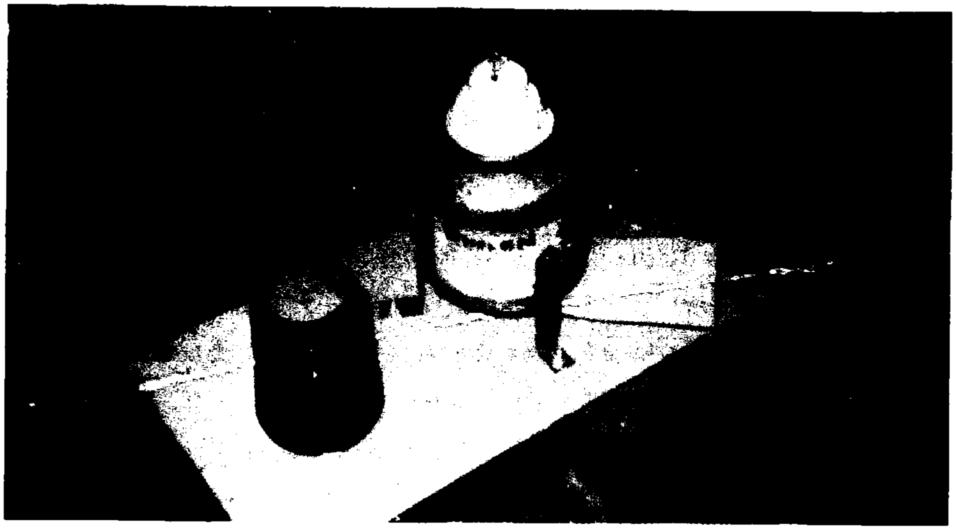
At this point the sensor unit was removed from the AENFTS test section and clamped to the AENFTS structure. Each false alarm source was positioned on the sensor's nominal incidence axis.

2. Aircraft Strobe Unit: A Whelen Aviation Lighting, Model A 470 strobe light head assembly with a Whelen HR,DF 200 power supply and A 402 lens (red) was used (Figure 8a). This unit produced a double pulse strobe flash at about 50 cycles per minute (it flashed twice followed by a pause with no light for each cycle). With the red lens it produced approximately 165 candlepower, and approximately 835 candlepower without the lens.

   The fire sensor's immunity to this flashing was checked with and without the red lens. The minimum distance at which it responded to the strobe was recorded in each case where there was a response.

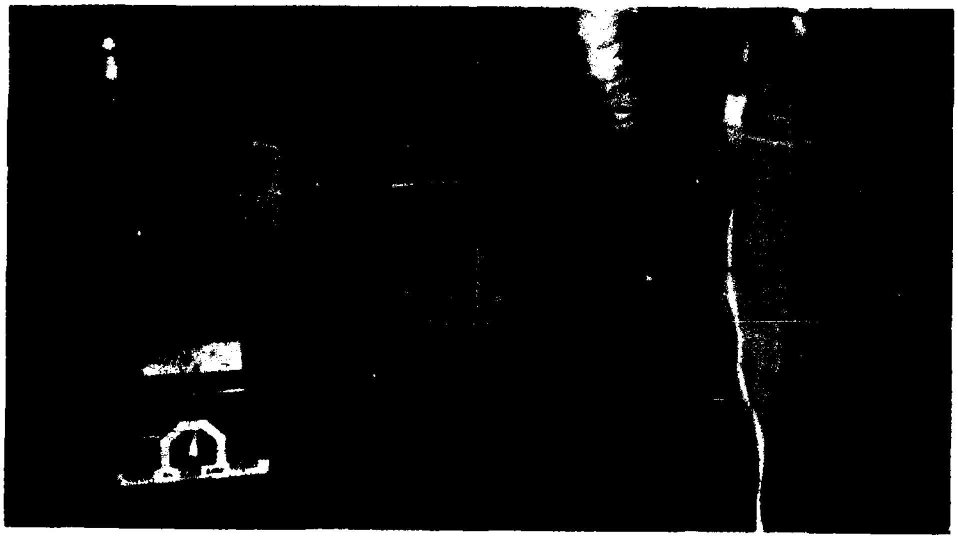
3. Simulated Hot Engine Bleed Duct: A six and one half inch segment of 1.40-inch diameter stainless steel rod, drilled to contain three cal rod heating elements (Figure 8b), was placed 64 inches from the sensor. This rod was heated first to 850°F, then to 1040°F and finally to 1200°F. Any incidence of a fire warning was recorded. At 1200°F, the hot duct was moved closer to the detector. The distance at which a fire warning was observed was recorded down to a minimum separation of about 12 inches. The sensor's response to the 1200°F bleed duct with the aircraft strobe light also operating was checked.

4. Electric Arc: An AC arc welder was operated and electric arcs were struck at distances of 9 and 5 feet from the sensor (Figure 8c). These tests employed a #8018 1/8 rod with the welding unit set for 160 amps which provided an erratic but powerful arc and a #6013 1/16 rod with the welding unit set for 130 amps which provided a more consistent electric arc. Any incidence of a fire warning was recorded.



a) Aircraft Strobe Light

b) Simulated Hot Engine Bleed Duct



c) Electrical Arc

*Figure 8. Optical Fire Detector False Alarm Test Devices*

# 3.0 TEST ARTICLE

The optical sensors being evaluated were supplied at no cost, although the baseline HTL/Graviner system had been developed under Air Force contract. The other four sensors employed one or more infrared (IR) detectors (in one case in combination with a UV sensor) and microprocessors to process detector inputs and provide a fire warning at some threshold of signal output. All were installed on the forward bulkhead of the F-16 nacelle simulator (Figure 9). The vendors were justifiably anxious to guard proprietary information and minimal description of system components and microprocessor logic was provided. The following information was approved by the vendors for public release.

## 3.1 Baseline HTL/Graviner Sensor

The HTL/Graviner sensor, as installed on the F-111 flight test airplane, employed 5 UV sensors on each engine, located in various fire zones around the engine compartment. The detector elements were coupled to microcomputers, one for each engine which gathered historical data, performed self tests and displayed system status on a single crew warning unit (CWU) in the cockpit.

The systems for the left engine and right engine were slightly different from each other. The system on the left engine, identified as system A, had dual detectors in each sensor to provide almost complete redundancy to improve reliability. The system on the right engine, system B, had a single detector in each sensor (Figure 10) and less redundancy to reduce costs. Details concerning this equipment are presented in Reference 5.

The simplified system installed in the AENFTS during 1983 and 1984, consisted of two sensors with a single detector in each sensor. One sensor was mounted in the normal location on the forward bulkhead of the F-16 nacelle simulator. A system B microprocessor computer control unit (CCU) was mounted on the AENFTS frame adjacent to the upstream end of the first test section. A second system B sensor was necessary for the CCU to operate, but this was placed in a closed container where it was shielded from the UV signal. The HTL/Graviner crew warning unit (CWU) was placed above the AENFTS viewing window where it could be monitored from the control room and where the sensors response to the test fires could be recorded on video tape. This simplified system was duplicated for the

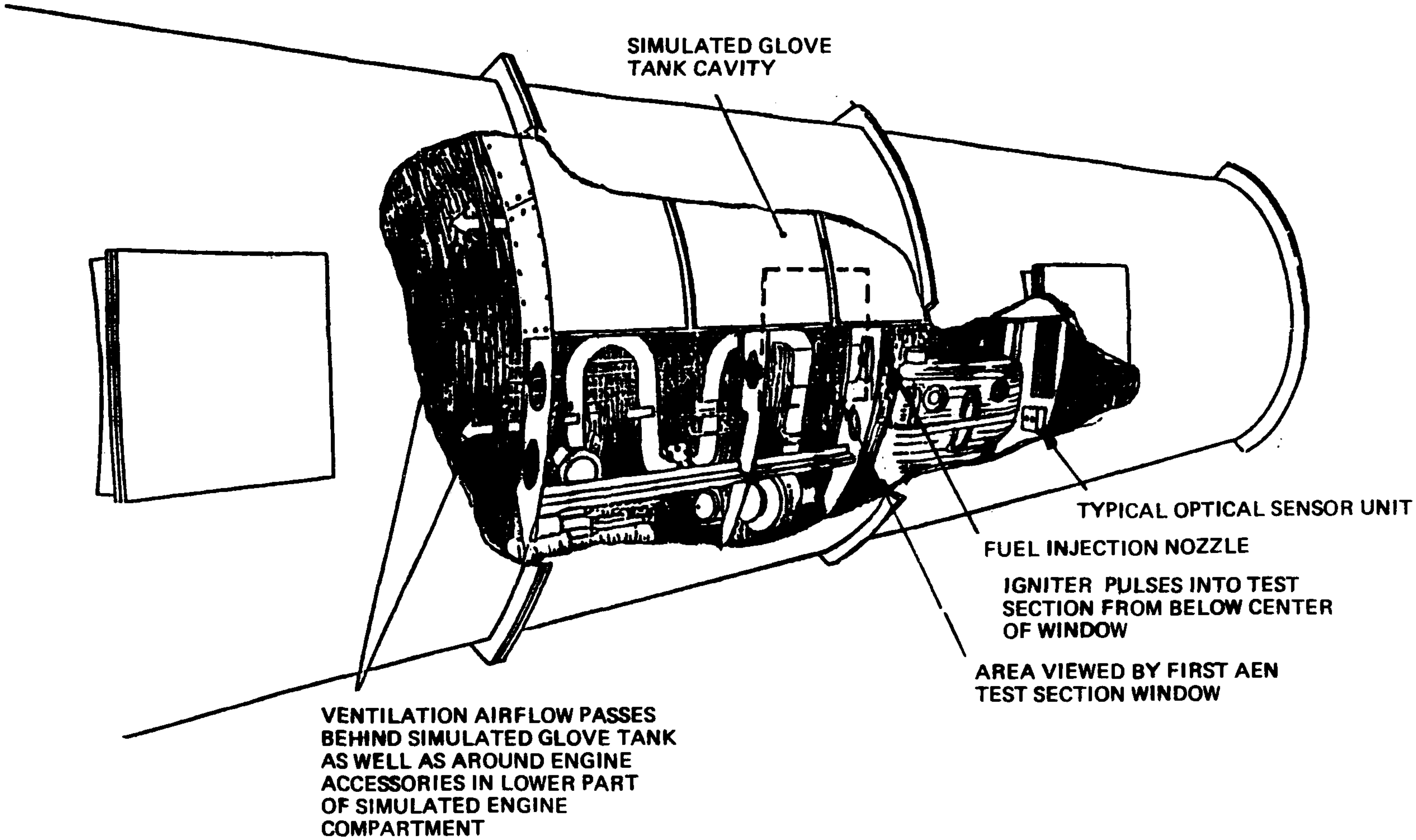



*Figure 9. Cutaway Diagram of F-16 Nacelle Simulator Installed in AENFTS*

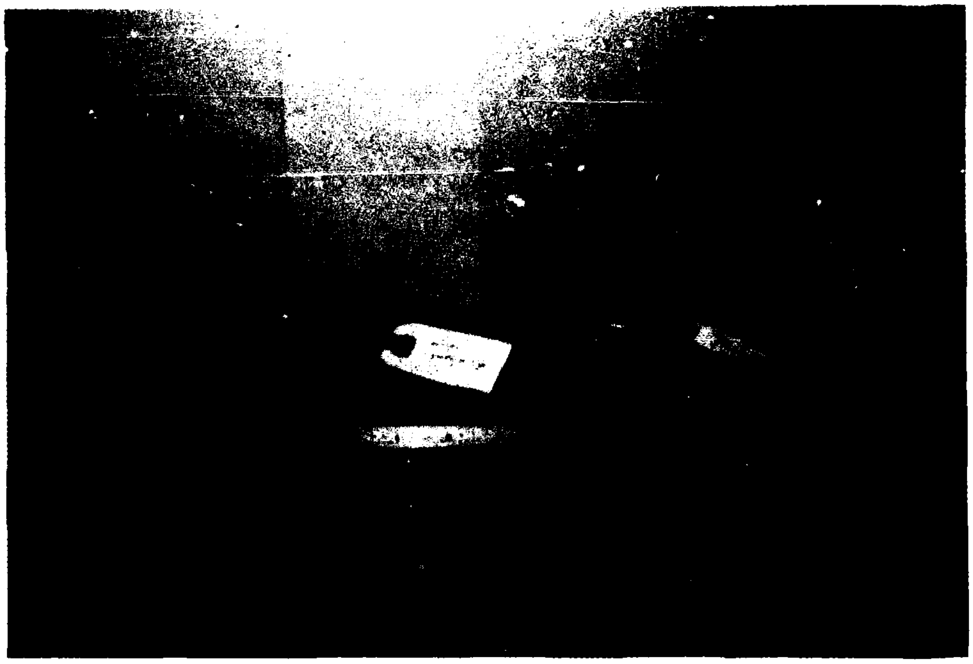


Figure 10. HTL/Graviner UV Sensor Unit

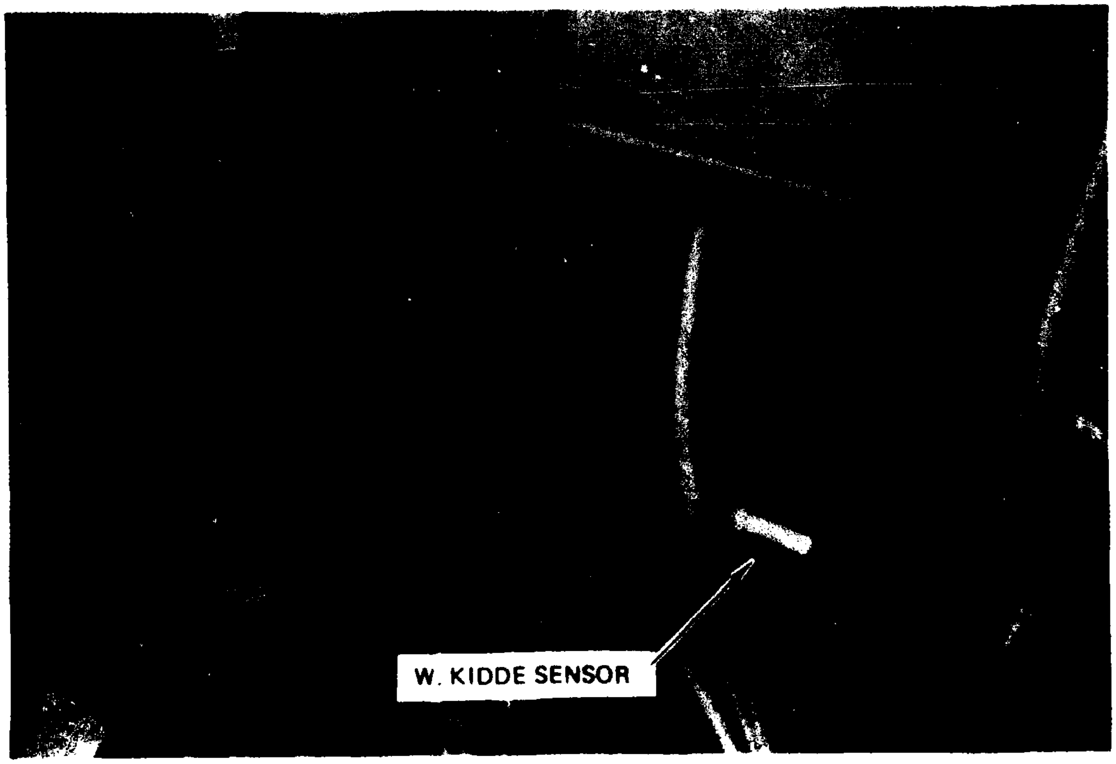



*Figure 11. W. Kidde Sensor Units Installed in AENFTS on Forward Bulkhead*

baseline tests. The HTL/Graviner sensor had a field-of-view approaching 360°F and an optical self-test feature. This sensor had been qualified to the MIL-STD-810 environment and an exposure to a 2000°F flame for one minute."

3.2 W. Kidde Sensor

The optical fire sensor which was provided for the first W. Kidde Company test entry during February, consisted of a dual channel sensor contained in a three-inch diameter by four-inch long cylinder with one channel responding to background in the 4 to 5 micrometer wavelength band and the other responding to background plus $CO_2$ emission in this same wavelength region. The field of view was about 53 degrees and was centered on the longitudinal axis of the sensor assembly. The fire signal threshold level was set in the Walter Kidde Optical Laboratory using the Army Tank Command standard fire, which is a 5-inch diameter flame pot, located 48 inches from the sensor. This assembly contained the necessary amplification and signal processing electronics to provide the remotely located control unit with analog signals and a fire signal. The fire indicating light was located in the lower left corner of the control unit assembly.

For the second test series during August, Kidde supplied two optical fire sensors, both of which were single channel IR units containing two detectors, both viewing the fire through a common narrow band filter. Within each, as with the unit provided during the first test series, one detector was designed to responded to $CO_2$ peaks and the other to broad band IR. Both units were installed on the forward bulkhead of the AENFTS'S F-16 nacelle simulator (Figure 11). One sensor had a hemispheric silicon dome with a field of view of 25 degrees. The other had a flat silicon window. Both were about 3 inches in diameter and about 5 inches long.

Each version of the two detectors contained one nitrogen and one carbon dioxide filled photodetector. Each photodetector output its signal to an amplifier circuit. Amplification was necessary to provide an adequate signal to the differential amplifier. Upon "seeing" a flame from the combustion of various hydrocarbons the output of the nitrogen gas filled photodetector became much larger than the output of the carbon dioxide filled photodetector. This caused the differential amplifier to output a large negative signal. This signal, upon reaching a preset level (voltage) set within the threshold circuit, triggered an alarm circuit.

The domed assembly "saw" along a single optical axis which was split just prior to each detector. The planar (non-domed) assembly, on the otherhand, "saw" along a single optical path for each photodetector.

Figure 12 is a sketch of the typical configuration showing a block diagram of the components. Each sensor is similar to the right of the indicating line. To the left of the line the components unique to the domed assembly are shown as indicated.

The field of view of the domed assembly was limited to approximately 50$^{o}$ (double angle) due to optical cutoff. The field of view of the planar assembly was limited to approximately 90$^{o}$ (double angle) due to cosine effect.

These assemblies both contained the necessary amplification and signal processing electronics to provide the remotely located control unit with analog signals and a fire signal. Either could trigger a simulated crew warning light which was installed above the main AENFTs viewing window (Figure 13) so that its signal could be recorded on video tape along with the fire. The sensor units were installed outside the AENFTS test section for the false alarm testing (Figures 14 and 15).

## 3.3 SBRC System

Santa Barbara Research Centers' optical fire detection system consisted of a dual channel IR sensor unit and an enunciator box which indicated the presence of a fire with fire warning lights. The sensor unit was 2 x 2 x 1.5 inches (Figure 16), and had a 90 degree solid cone angle field of view.

Three interchangeable sensors were evaluated, the most sensitive being installed on the forward baffle plate
in the AENFTS's F-16 nacelle simulator. The other two were installed in access plates downstream of the simulator, one in the small window in the top of the middle test section, 36 inches aft of the fuel nozzle and igniter, and the other in the side window of the same test section.

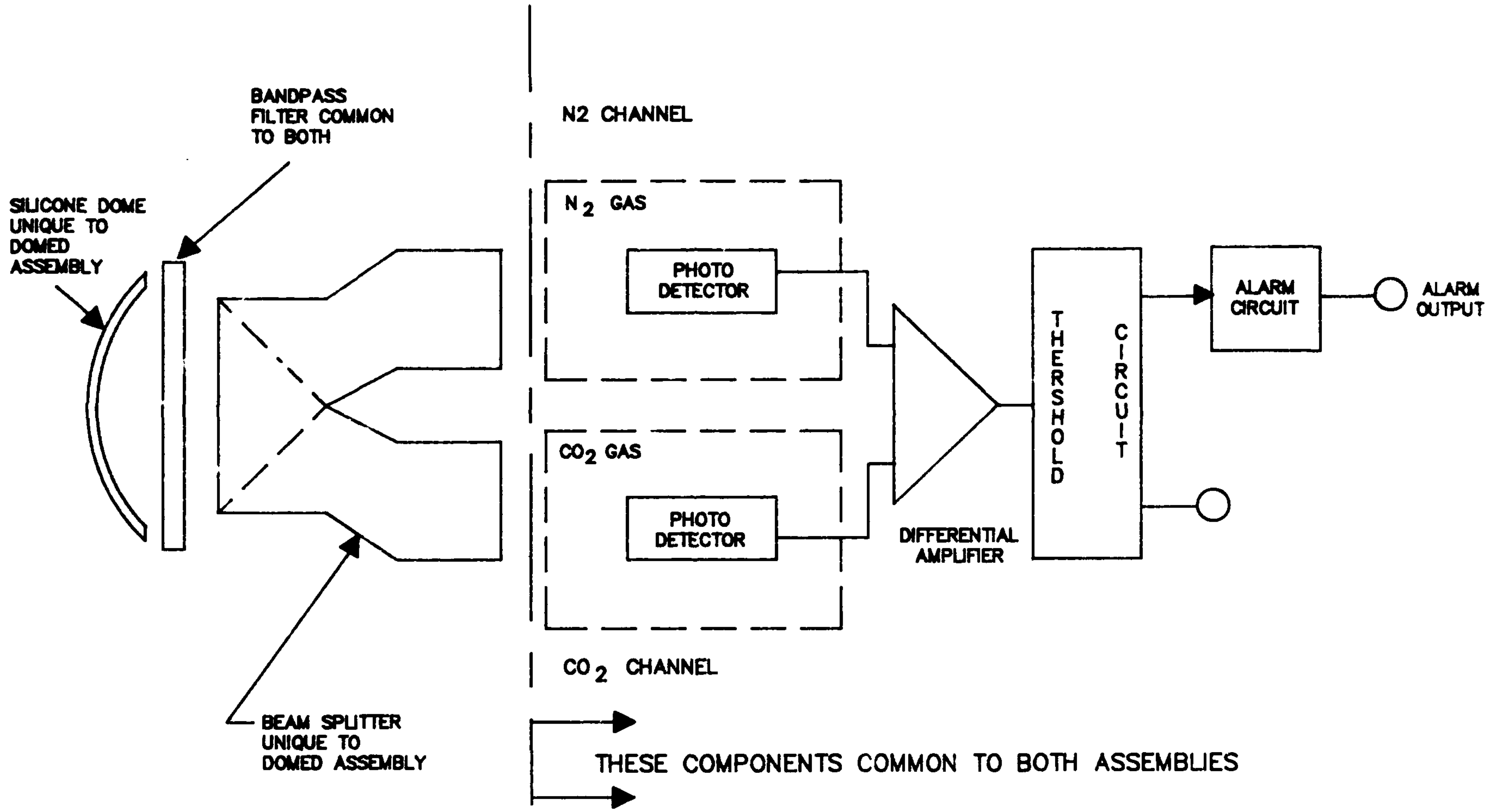



*Figure 12. Typical Configuration of W. Kidde Optical Detector*

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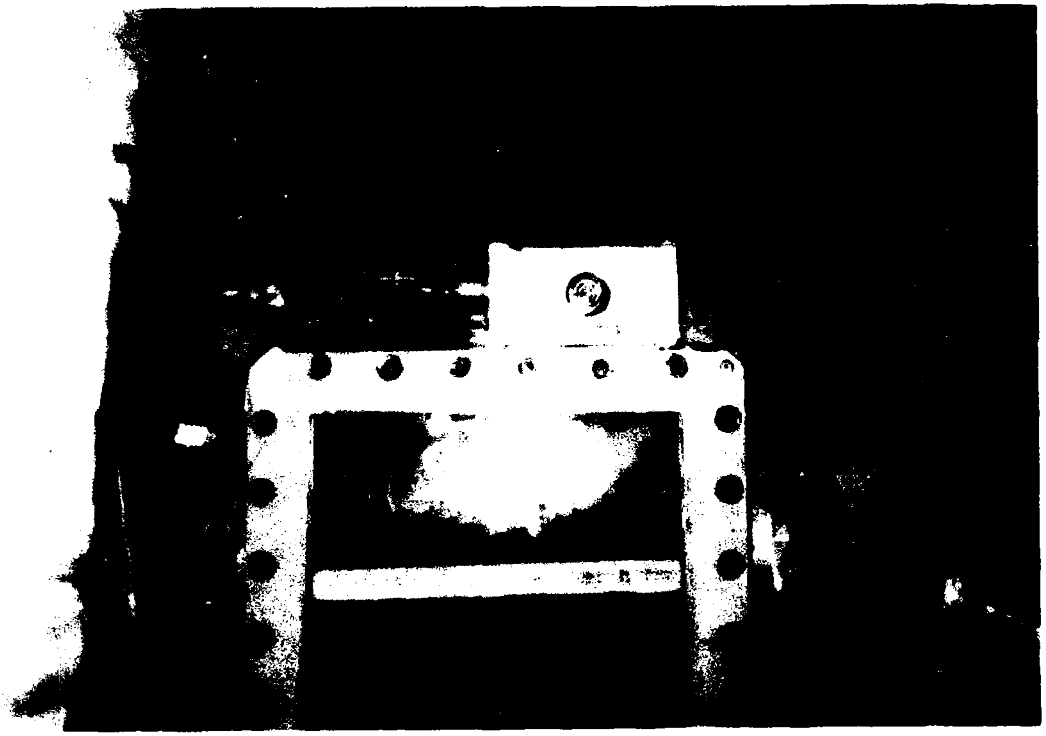

*Figure 13. CWU for W. Kidde System Installed Above AENrTS Viewing Window*

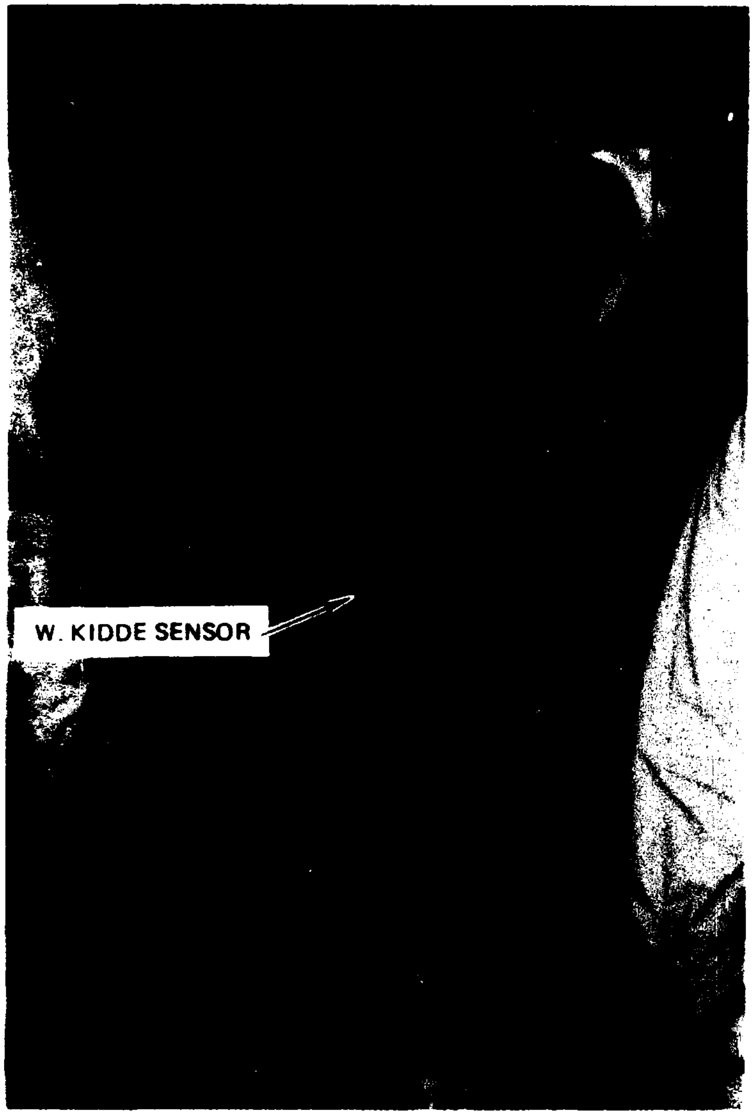


*Figure 14. W. Kidde Sensor Unit, Front View*

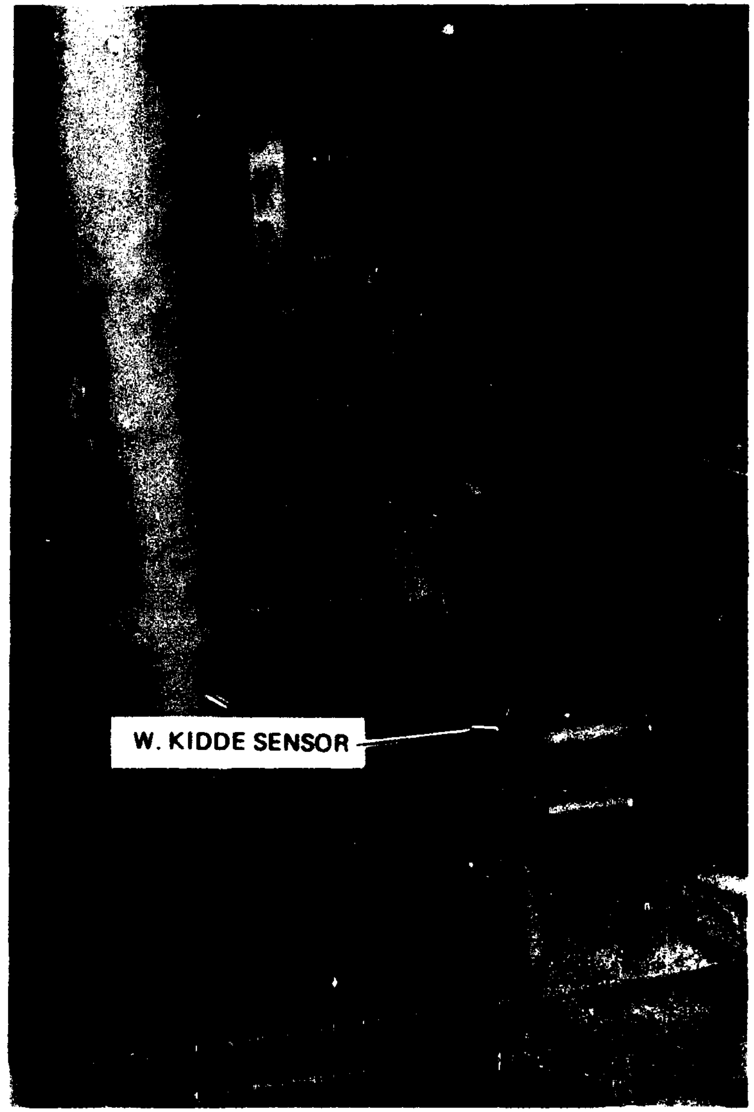


*Figure 15. W. Kidde Sensor Unit, Side View*

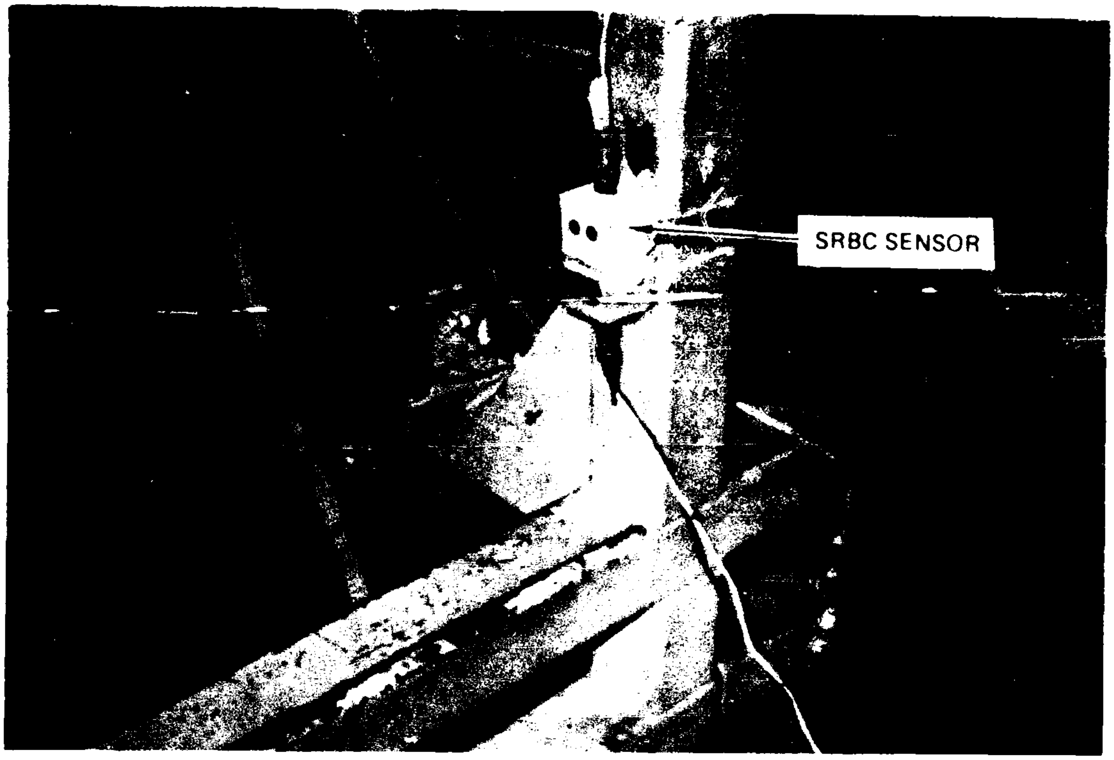


*Figure 16. Two SRBC Sensor Units*

Due to mounting restrictions in the AENFTS test section, all sensors were separated by a bulkhead from the section where the fuel nozzle was located. The upstream view of the fires was limited to two 1.5 inch holes in the bulkhead. The downstream sensor locations were similarly obscured from viewing the test fires, except that flames from the 31.2 GPH fires penetrated the bulkhead openings.

Referring to the functional block diagram in Figure 17, the sensors were dual spectrum units with one detector that responded to short wave lengths (below 1 micron) and the other to long wavelengths (above 6 microns). The sensor system contained the necessary amplification and signal processing electronics to provide the remotely located enunciator unit with a fire signal.

The sensors, which were designed for and used during the Wright-Patterson Air Force Base Dry Bay Test Program (Ref.6), used AND gate logic with inputs from each wavelength sensitive detector. Signal processing circuitry associated with each cell incorporated a separate threshold prior to the AND gate.

Also, each sensor system had its own power conditioning, built-in-test (BIT) and valve driver circuitry. Power conditioning included both voltage regulation and lockout circuits to avoid detector responses to line transients up to 800 volt spikes.

BIT was incorporated as an "interogate BIT" where a pulse sent in on pin D generated a responding pulse on pin C only if the detector was fully operational. The valve driver was a capacitive discharge circuit designed to drive up to four squib valves. This valve driver was locked out during the BIT mode.

In addition to the system used in the test program, SBRC brought a radiometer system which was installed in a specially constructed adapter in the viewing window that was directed at the forward portion of the test fires. This equipment was removed once the radiometer testing was completed and was not part of the sensitivity or the false alarm test installation.

SBRC stated that the detector units had been designed to operate in high temperature environments, hence the units installed downstream of the F-16 simulator were in locations close to and actually enveloped in the test fire.

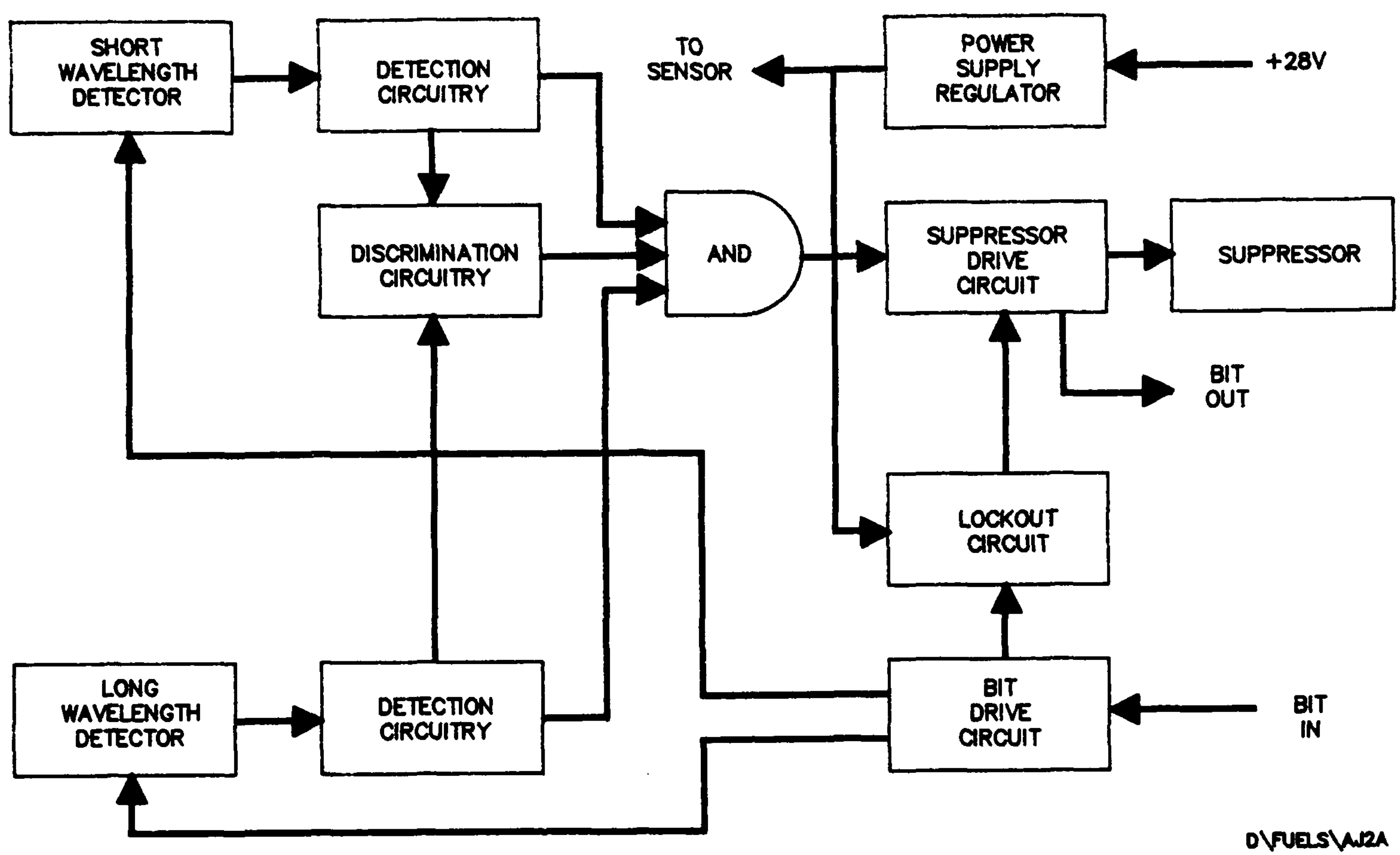


Figure 17. SBRC Sensor Functional Diagram

## 3.4 Armtec System

The Armtec optical fire detection system consisted of a sensor unit and a control unit containing a microprocessor. The control unit was mounted on the AENFTS frame adjacent to the upstream end of the first test section. The sensor was about 2 x 2 x 1.5 inches and had three small domes covering the detectors (Figure 18), all protected by a metal screen. A terminal strip on the control box provided electrical connections for a cockpit crew warning unit with adjacent red fire, amber "fault" and green "system ready" lights and connection to a 28-volt power supply (Figure 19). Boeing provided a red and a green light on a mounting bracket above the main AENFTS viewing window so that the control box fire and "system ready" output signals could be included in the video tape data record.

Referring to Figure 20, Armtec has described the detector unit as containing three optical detectors which monitored, respectively, broad band IR signal, narrow band IR signal centered on the $CO_2$ emission and the shorter UV wavelengths. Outputs from these three detectors were monitored by the microprocessor and its internal logic established combinations of signals that would allow for determination of a fire condition with maximum discrimination (i.e. actual fire versus false alarms).

The Armtec system functioned as intended during the entire test period. No test time was lost due to redesign, repair or replacement of the Armtec equipment.

## 3.5 Pyrotector System

The Pyrotector optical fire detection system consisted of a cylindrical sensor unit mounted in the normal position on the forward bulkhead of the F-16 nacelle simulator, connected to a box mounted above the AENFTS viewing window. The sensor was 2.5 inches in diameter, 1-1/16 inch long and had a flat sapphire lens covering the detectors. The unit contained batteries, a microprocessor, a visible simulated crew warning light and reset switch (Figure 21). When a fire warning was displayed, it was locked on until the reset switch was operated.

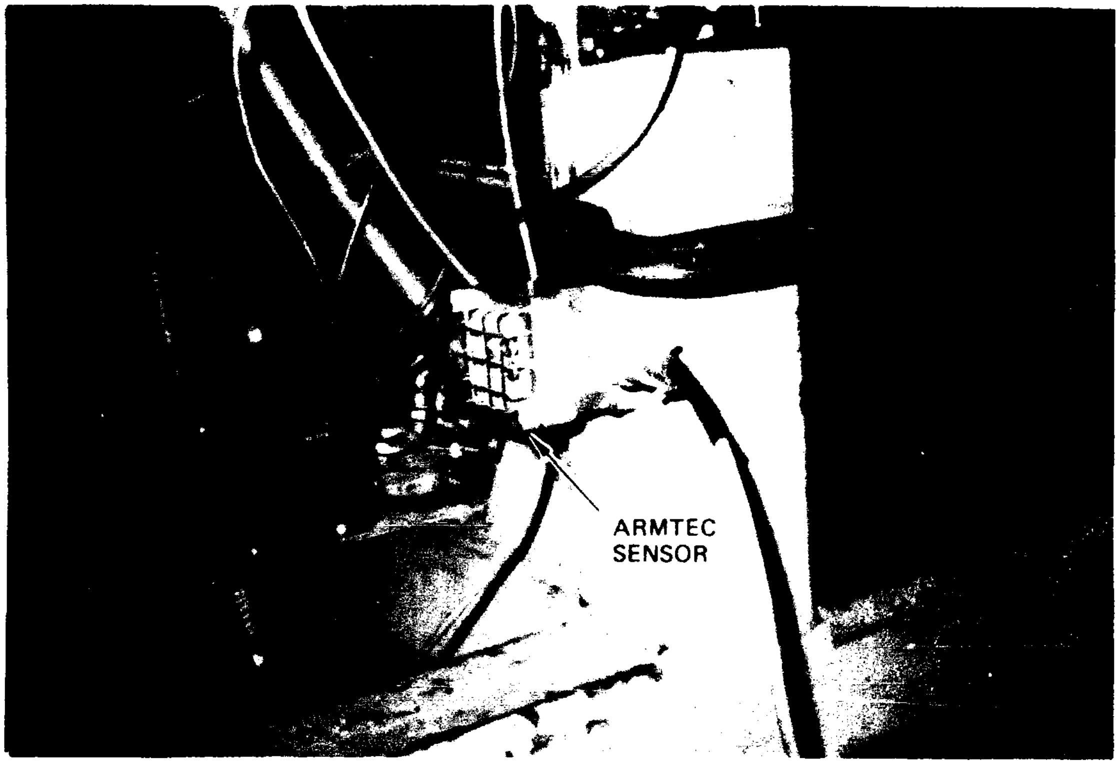


*Figure 18. ARMTEC Sensor Unit*


*Figure 19. ARMTEC Sensor and CWU*

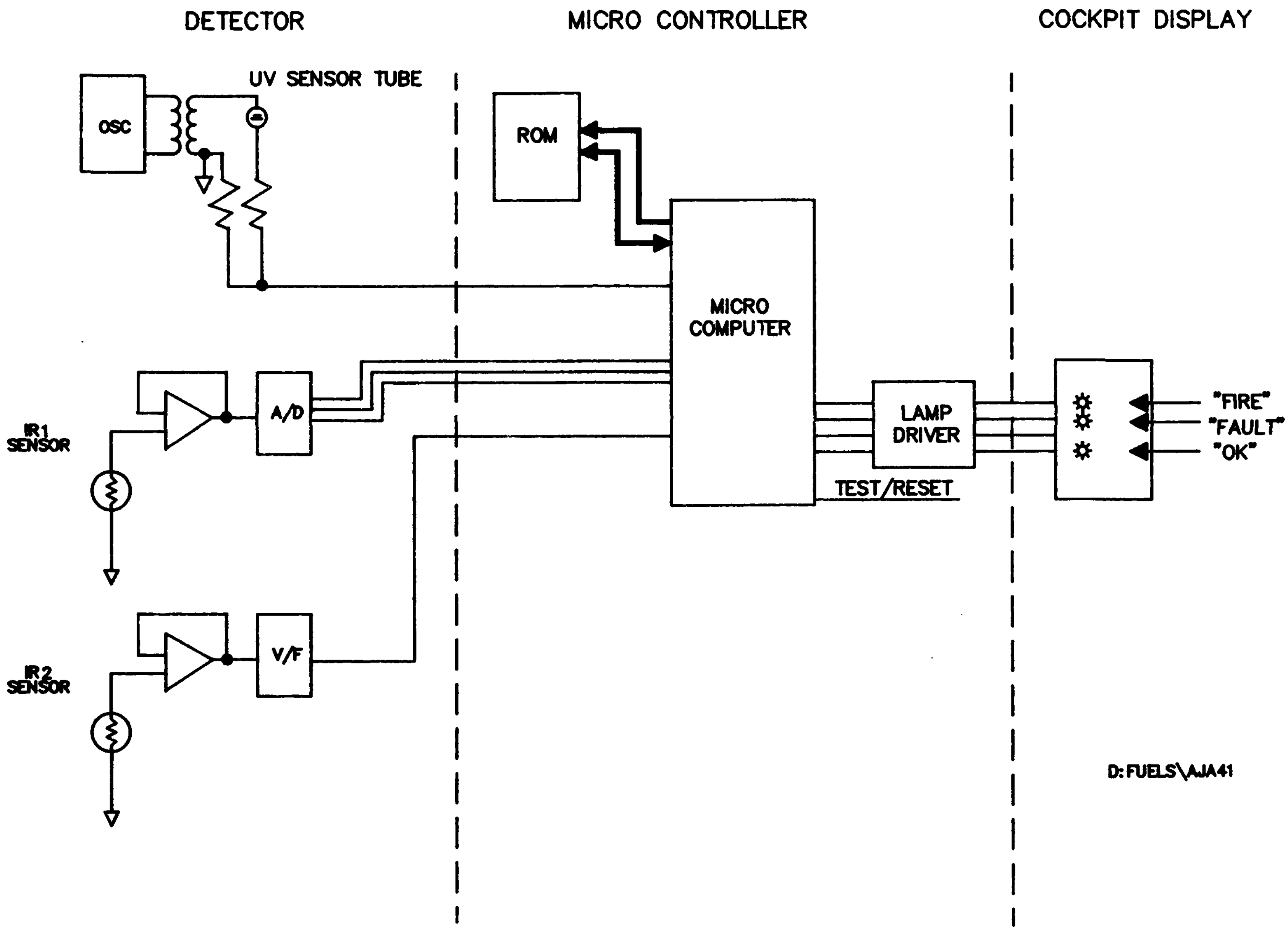


Figure 20. Block Diagram of Armtec Optical Detector

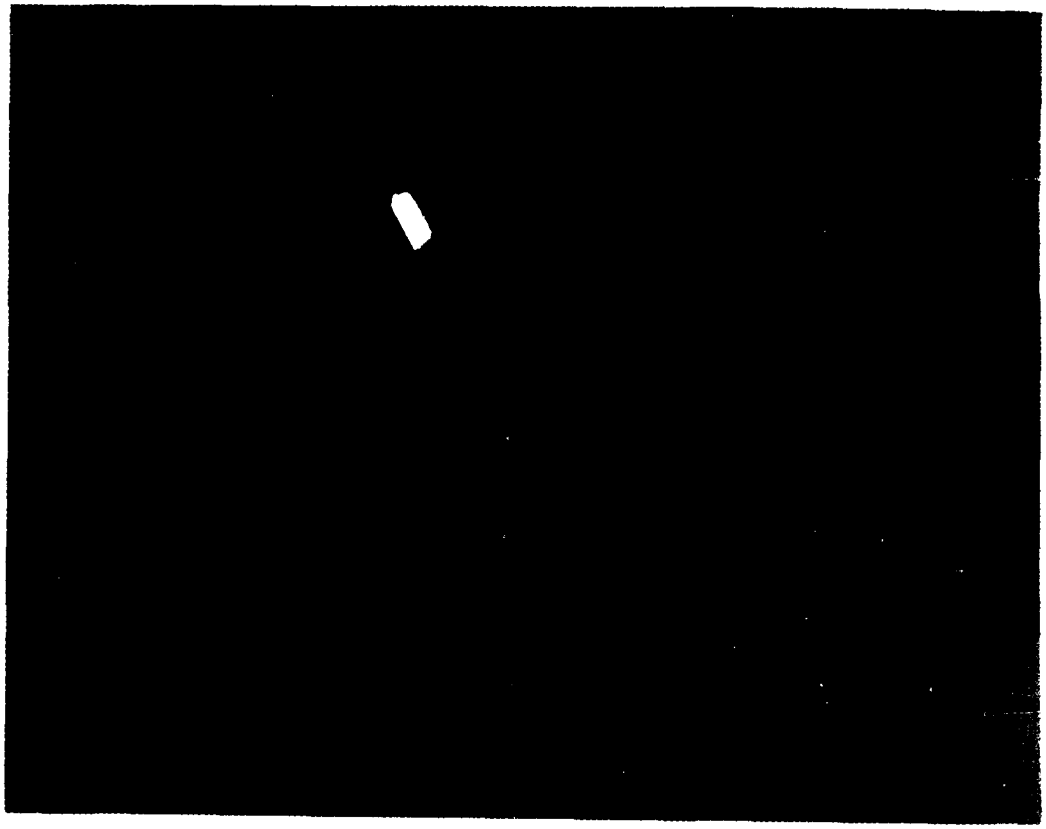

*Figure 21. Pyrotector Detector Unit*

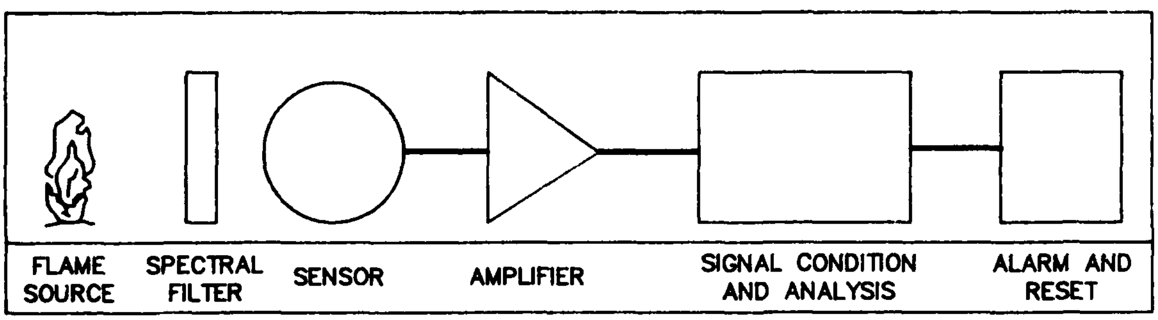


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*Figure 22. Block Diagram of Pyrotector Optical Detector*

A block diagram of the Pyrotector system is shown in Figure 22. Pyrotector reported that the sensor contained a narrow band IR detector specially filtered to exclude all non-fire radiation. They also stated that the flicker content of the fire affected the response time of the sensor. Pyrotector explained that its approach was highly proprietary and depended on specially developed spectral filtering as well as sensor technology and electronics exclusive to Pyrotector.

The Pyrotector equipment, which had no need for external power supplies functioned as intended during the entire test period. No test time was lost due to redesign, repair or replacement of the Pyrotector equipment.

3.6 Suitability of the Sensors to an Aircraft Engine Nacelle Environment

The HTL/Graviner system was validated in flight tests on an F-111 aircraft (Appendix A) and has been in service on that airplane for seven years. The other prototype sensors tested had not attained this maturity at the time of this test program.

Electronic components (e.g. photodiode detectors, op-amps and diodes) are limited currently to temperatures below 250°F. Battery power for the detectors, although appropriate for the AENFTS, would probably be replaced by an aircraft power source in an actual installation. Since all prototype detector systems except the HTL/Graviner system, had some solid state electronic components, their ability to function properly at environmental temperatures approaching 500°F needs verification. Thermal insulation can minimize high temperature problems as was demonstrated (but not qualified) during this test program. Furthermore, no tests were conducted to evaluate the durability of the prototype systems.

# 4.0 RESULTS

Sensitivity and false alarm test results are presented in Table 4. The Pyrotector sensor was the only prototype sensor that responded to every fire and ignored all false alarm signals. The HTL/Graviner system responded to all fires for engine compartment pressures, temperatures and airflow rates typical of current aircraft. The HTL/Graviner system did respond to arc welding but this false alarm source is unlikely when the detection system is activated. The Armtec sensor did not respond to any of the false alarm signals but did miss one fire under realistic, simulated flight condition.

Although 300°F ambient airflow tests were conducted, the thermal history of each of the sensor housings was not measured. As a result, it is unclear whether thermal equilibrium was reached during these tests.

## 4.1 Sensitivity Testing

### 4.1.1 Baseline Tests with HTL/Graviner System

With the smaller 1 GPH fires, the HTL/Graviner detector provided a fire warning for six out of the seven planned test conditions. This included all but the highest simulated engine compartment airflow rate and ram air pressure (2 lbs/sec at 24 psia), a condition not encountered on current aircraft but projected for advanced aircraft. The sensor usually responded about one second after the fire was ignited. For another (1 lb/sec at 20 psia) about six seconds elapsed before the fire warning light indicated the presence of a fire. In all the other tests, the fire warning light came on about one second after the fire was ignited and remained on without flicker until about one second after the fire was extinguished.

With the larger, 31.2 GPH fires, the detector provided a fire warning for every fire. Again, the fire warning light came on about one second after the fire was ignited and remained on without flicker until about one second after the fire was extinguished.

## Table 4. *Summary of Test Results*

SENSITIVITY TESTING

| TEST NO. | NOMINAL VENT'N AIRFLOW (LB/SEC) | NOMINAL TEST SECTION PRESS (PSIA) | NOMINAL TEST SECTION TEMP. (DEG. F.) | JP-4 FLOWRATE (GPH) | DETECTOR SYSTEM'S RESPONSE TO FIRE: BASELINE GRAVINER UV | ARMTEC | W. KIDDE 2ND ENTRY | SBRC | PYROTECTOR |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.00 | AMB | 100 | 1.0 | YES | YES | NO | NO | YES |
| 2 | 2.50 | AMB | 100 | 1.0 | YES | YES | NO | NO | YES |
| 3 | 0.50 | AMB | 100 | 1.0 | YES | NO | YES* | NO | YES |
| 4 | 0.50 | 7.0 | 100 | 1.0 | YES | YES | YES | NO | YES |
| 5 | 1.00 | 10.0 | 100 | 1.0 | YES | YES | YES | NO | YES |
| 6 | 1.00 | 20.0 | 100 | 1.0 | YES** | YES | YES | NO | YES |
| 7 | 2.00 | 24.0 | 100 | 1.0 | NO | NO | YES | NO | YES |
| 8 | 1.00 | AMB | 300 | 1.0 | YES | YES | YES* | NO | YES |
| 9 | 1.00 | AMB | 100 | 31.2 | YES | YES | YES* | YES* | YES |
| 10 | 3.50 | AMB | 100 | 31.2 | YES | YES | YES* | YES* | YES |
| 11 | 6.00 | AMB | 100 | 31.2 | YES | YES | YES* | YES* | YES |
| 12 | 0.50 | 7.0 | 100 | 31.2 | YES | YES | YES | YES* | YES |
| 13 | 1.00 | 10.0 | 100 | 31.2 | YES | YES | YES | YES* | YES |
| 14 | 2.00 | 24.0 | 100 | 31.2 | YES | YES | YES* | YES* | YES |
| 15 | 6.00 | 24.0 | 100 | 31.2 | YES | YES | YES* | YES* | YES |
| 16 | 1.00 | AMB | 300 | 31.2 | YES | YES | YES | YES* | YES |

* OCCASIONAL OR BRIEF FLASHES
** LONG DELAY

FALSE ALARM TESTS

| | | | | | | |
|---|---|---|---|---|---|---|
| 1 | SIMULATED HOT ENGINE SOAK | NO | NO | NO | NO | NO |
| 2 | HOT ENGINE BLEED DUCT | NO | NO | NO | NO | NO |
| 3 | AIRCRAFT STROBE LIGHT WITH RED LENS | NO | NO | NO | NO | NO |
| 4 | AIRCRAFT STROBE LIGHT WITHOUT RED LENS | NO | NO | NO | NO | NO |
| 5 | COMBINED BLEED DUCT AND STROBE LIGHT W/RED LENS | NO | NO | NO | NO | NO |
| 6 | COMBINED BLEED DUCT AND STROBE LIGHT W/OUT RED LENS | NO | NO | NO | NO | NO |
| 7 | ELECTRICAL ARC; 160 AMPS WITH 1/8" ROD | YES | NO | NO | NO | NO |
| 8 | ELECTRICAL ARC; 130 AMPS WITH 1/16" ROD | YES | NO | NO | NO | NO |

4.1.2 W. Kidde Company System Testing (First Series)

During initial tests employing the atmospheric pressure blower at 1.0 lb/sec and the 1.0 GPH nozzle, the sensor failed to respond to any of three test fires. At the request of the Kidde representative, the test section was opened and the sensor was rotated 180 degrees. With the sensor in this position, the atmospheric pressure tests were repeated with the 1.0 GPH nozzle and the 31.2 GPH nozzle. Fire warnings were observed for all but the highest airflow (3.5 lbs/sec) fires with the 1.0-GPH nozzle installed.

The Kidde representative elected to omit the altitude and ram simulation tests at that time and concentrate on further investigation into the effects of sensor rotation and other sensor sensitivity problems. Hence the atmospheric blower sensitivity tests were repeated with the 1.0-GPH nozzle and 1.0-lb/sec airflow while the sensor was rotated in its base to several other positions. Several other problems were identified during these tests.

It was determined that one channel of the sensor was excessively noise sensitive and it was observed that operation of the high-flow/low-flow switch on the AEN control console consistently caused the system to indicate the presence of a fire. Kidde requested that they be allowed to terminate this test period and allowed to return and try again once they had analyzed their problems and developed modifications that would correct them.

4.1.3 W. Kidde Company System Testing (Second Series)

Initially, during preliminary tests with the smaller fuel nozzle and 1 lb/sec airflow, a few problems were encountered with AENFTS instrumentation, the ModComp computer and visibility of the the fire warning light that Kidde supplied on the control console TV monitor. Once these were corrected, several more preliminary tests were performed with this fire size and flow rate.

Momentary flickers of the fire warning light, usually at the start and end of the fire tests were observed. The Kidde sensors appeared to still be sensitive to the use of the high-flow/low-flow switch on the AENFTS control console. Tests were conducted to examine whether this was electrical interference or sensitivity to pressure changes and they indicated the latter.

The Kidde engineers examined the data they had acquired and decided that a further try at pressure sealing the sensor bodies was necessary. An attempt at sealing these with Permatex RTV Silicone Gasket material was made. They also concluded that sensitivity of the sensors was acceptable and that all components were working properly. Following this the planned sequence of sensitivity tests was conducted.

As testing progressed, the detector still responded to ventilation airflow rate change with a brief fire warning light but did not otherwise indicate any presence of fire. On the third of these tests, a ventilation flow rate of 0.5 lbs/second, the fire warning light did respond briefly, a fraction of a second after the fire was ignited. Since the light went out and remained out during the duration of the fire, the sensor was probably responding to the ignition overpressure and not to the fire's optical radiation.

During the first simulated altitude test (7 psia test section pressure) with a fuel flow rate of 0.5 lbs/second, the fire indicator flashed steadily during the entire period that the fire was ignited. During the next altitude test (10 psia test section pressure) 1.0 GPH fuel flow rate and 1 lb/second ventilation airflow rate, the sensor again flashed briefly just after the fire was ignited, again perhaps due to overpressure.

Last were two 1.0 GPH high pressure (ram simulation) runs, 1 lb/sec at 20 psia and two lbs/sec at 24 psia. With these tests also, the sensor responded initially as the fire was ignited and then went out and remained out during the remainder of the test. The Kidde crew attempted further pressure sealing prior to continuing the sensitivity testing.

The sensitivity tests with 31.2 GPH fuel flow were completed next. The later sealing attempt seemed to eliminate the sensor's sensitivity to airflow rate changes. However, during the first two tries with 1.0 lb/min of ventilation airflow at atmospheric pressure, the sensor failed to provide any fire warning even though these were substantially larger fires than those run earlier. The sensors were rotated in their bases and on the third try, a brief flash was noted just after the fire was ignited. The planned sensitivity tests with the 31.2 GPH nozzle were repeated with the sensors repositioned and the sensors responded to all to some degree, in some cases a brief flash at the start and in some a steady fire light during the entire test.

The last two test conditions employed heating the ventilation airflow to 300°F so that potential damage to the detectors or wiring did not influence subsequent test results. These involved 1 lb/sec airflow at ambient pressure and 31.2 GPH and 1-GPH fuel flows. With the larger fuel nozzle there was a steady fire light during the test, with the smaller nozzle there was a brief initial flash.

The question of whether the "brief flash" warnings had been a response to IR radiation from the fire or overpressure from its ignition was addressed on completion of the sensitivity tests. Both sensors were mounted outside the AENFTS test section in preparation for the false alarm testing. A hand-held pistol type propane torch was positioned at distances from one to three feet from the sensors. When the torch was close to the sensors, the fire warning light came on and remained on as long as the torch was lit. When the torch was about three feet from the sensors, the fire light would come on only briefly as the torch was lit and did not remain on even though the torch remained lit and in the same position. Hence it is probable that the "brief flash" warning seen during the later tests was due to IR radiation from the flame and not combustion overpressure. Because additional sealing work was performed at various times during the testing, whether all the responses were due to IR radiation is uncertain.

### 4.1.4 Santa Barbara Research Center (SBRC) System Testing

Detectors designed for use in engine nacelles were still under development by SBRC at the time of AEN testing, but were scheduled to be ready for the next phase of testing to be conducted at the FAA Technical Center. Rather than not participate in this program, SBRC chose to submit sensors for testing that were optimized for other applications. In this manner they could assess the critical factors of engine compartment fire protection and thus be better qualified to develop sensors suitable for the F-111 test rig.

Sensitivity tests, employing 1-GPH and 31.2 GPH fuel flow fires, were conducted with the SBRC sensors installed in the AENFTS and the results were quite consistent. All three of the SBRC sensors provided a fire warning for all of the 31.2 GPH fires. However, the number 1 sensor performed erratically during the last three tests (fire warning lights flickered on and off). SBRC indicated that this was normal, and that the output of these sensors would "vary with the

AC component of the flame." All three of the SBRC detectors failed to provide a fire warning for all of the 1-GPH fires, at all ventilation flowrates and pressures.

Following test condition 14, a low airflow (2 lbs/sec), high pressure (24 psia) test, the number 1 sensor continued to indicate a fire until well after the fire had been extinguished. During the next test, a high airflow (6 lbs/sec) test, run at atmospheric pressure with 1 lb/sec airflow and with the airflow heated to 300°F, the unit appeared to operate normally initially but then appeared to fail after about five seconds.

SBRC initially concluded that the number 1 sensor had been damaged during its extended exposure to its high temperature environment (reaching about 2000°F on test condition 14 after being exposed to the fire) and that on-site repairs were not feasible. After removal from the AENFTS Simulator, it was noticed that the number 1 sensor was covered with a very thick layer of hard soot from immersion in flames from the 31.2 GPH conditions and did not respond to test flames as the other sensors did. Later, when the soot layer was cleaned from the windows, the number 1 sensor was found to be still operational.

#### 4.1.5 Armtec System Testing

With the 1-GPH fuel flow fires, the Armtec detector provided a fire warning for five out of the seven test conditions. This included all but the lowest airflow sea level test (0.5 lbs/sec at 14.1 psia) and the higher airflow/ram air pressure simulation test (2 lbs/sec at 24 psia). The fire warning light flickered during two of the test conditions where it indicated a fire, the intermediate airflow sea level test (2.5 lbs/sec at 14.4 psia) and the lower airflow/ram air pressure simulation test (1 lb/sec at 20 psia). The test was repeated because the air temperature was 83°F rather than 100°F as planned during the latter test. With the air temperature at 100°F the flicker was no longer present.

With the 31.2 GPH fires, the sensor provided a fire warning for every fire. With the highest airflow sea level case (6 lbs/sec at 15.5 psia) the fire warning light flashed on and off during the fire. With the lowest airflow altitude condition (0.5 lbs/sec at 7 psia) the warning light flashed on and off several times before remaining on for the duration of each fire.

The time delay between ignition of the fire and the appearance of the red warning light varied from 0.3 to 1.9 seconds, and apparently was not a function of the fire intensity.

### 4.1.6 Pyrotector System Testing

Unlike other systems evaluated during this test program, the Pyrotector system responded to every fire.

The time delay between ignition of the fire and the appearance of the fire warning light varied from about one to four seconds. No information was available concerning when the detector ceased to indicate a fire, since the fire warning light was locked on as soon as it was displayed.

## 4.2 False Alarm Testing

### 4.2.1 Baseline Tests with HTL/Graviner System

With the HTL/Graviner sensor mounted in its normal position on the forward inlet bulkhead of the F-16 nacelle simulator, the simulated hot engine soak did not cause a false alarm. The sensor indicated a fire warning only while the fire was present. Once the fuel injection was terminated the fire warning light went out as the fire decreased in size to a few flickers of residual fuel. No false alarm was observed during the soak period.

The remaining false alarm tests were performed with the sensor outside the AEN test section, clamped to a structural upright. Neither the simulated hot engine bleed duct at 1200°F nor the aircraft strobe light cause a fire warning, even when combined at a distance of 12 inches from the detector.

Electric arcs generated with both the #8018 1/8 welding rod and the #6016 1/16 welding rod caused the sensor to indicate a fire within about one second of the arc being struck, even at nine feet from the sensor. In both cases if the arc was pulsed so that its duration was less that one second, followed by a pause of about the same duration, the detector did not indicate a fire.

### 4.2.2 W. Kidde System Testing (First Series)

The W. Kidde sensor was insensitive to the simulated hot engine soak, the aircraft strobe light with or without its red lens and to electric arcs. With the simulated hot engine bleed duct at 1200°F, a fire warning was seen at a distance of 28 inches from the detector. The test was repeated twice and the fire warning occurred at 28 inches (within 1/2 inch) all three times.

### 4.2.3 W. Kidde System Testing (Second Series)

During the second test entry, the Kidde sensor was totally insensitive to the false alarm signals. While the system responded to the simulated hot engine bleed duct at 1200°F at a distance of 28 inches from the detector in the unit was totally insensitive during the second test series. The unit continued to be unaffected by the aircraft strobe light and electric arcs, at any distance. Since the system had been completely insensitive to the hot engine soak test during the first series, this test was unnecessary.

### 4.2.4 Santa Barbara Research Center System Testing

Because the SRBC number 1 sensor was assumed to have been damaged in the last of the sensitivity tests, the false alarm testing of the SBRC system was limited to the number 2 and number 3 sensors. No false alarm was noted with either the simulated hot engine soak test or the simulated hot engine bleed duct test.

The number 2 sensor was totally insensitive to the aircraft strobe light, with or without its red lens, down to a minimum distance of 12 inches. The more sensitive number 3 sensor provided a fire warning when the red lens was used, at distances of 64, 32 and 12 inches; it did not give a fire warning without the red lens at a distance of 64 inches, but did at 32 and 12 inches. When the strobe unit was operated with its red lens at the same time as heated bleed duct, the number 3 sensor did indicate a false alarm but the number 2 sensor did not.

Electric arcs caused no false alarms, with either type of welding rod or at any distance.

### 4.2.5 Armtec System Testing

The Armtec sensor also performed perfectly in the false alarm tests. It was interesting to note that when the aircraft strobe unit was operated with its red lens, by itself or in addition to the hot bleed duct, the strobe's flashing did cause the green "ready" light to flash on and off at distance between 16 inches and 64 inches. Since no fire warning was observed, this was not interpreted as a false alarm. In all the other false alarm tests, including the simulated hot engine soak, the simulated hot engine bleed duct and the arc welding, the unit provided neither a false fire warning nor a flashing green "ready" light.

### 4.2.6 Pyrotector System Testing

The Pyrotector system also passed all the false alarm tests. These again included the simulated hot engine soak test, the hot engine bleed duct simulator heated to 1200°F, the aircraft strobe light (with or without its red lens) within 12 inches of the detector and the electric arcs generated with either the 1/16-inch or the 1/8-inch welding rods.

## 5.0 ANALYSIS OF RESULTS

The participating fire detection system vendors were understandably reluctant to endanger their competitive positions by being completely open about the design details of their systems. Some details were provided, however, which allowed limited analysis of the results in terms of the advantages of their approaches to the problem of identifying the optical signals from small simulated engine compartment fires relatively far from the sensors, while remaining immune to the false alarm optical signals.

### 5.1 Sensitivity

In the baseline tests, the HTL/Graviner UV sensors had good sensitivity during the atmospheric blower (high pressure ram air) and altitude tests. While the video tape records of ram air pressure simulation tests indicate equally visible fires, the sensor had some difficulty responding to the UV components emitted. One test fire was not detected at all, and a second required six seconds for the detector to respond rather than the usual one second. The HTL representative agreed that the higher density air attenuated the UV signal and that this has less effect on IR signals.

The Armtec and Pyrotector systems performed better than the baseline system. The Armtec sensor which had three optical detectors, examined a narrow radiation band centered on the wavelength of $CO_2$ emissions (IR), a broad band IR signal, and the shorter wavelength UV emissions. The Pyrotector system was said to be examining more than one band of IR emissions. In both cases the sensitivity was as good as the HTL/Graviner UV unit.

The denser air which existed in the test section during high pressure ram simulation tests did not seem to inhibit either the Armtec or the Pyrotector sensor's ability to identify even the smallest fires. The Armtec sensor responded to five out of seven of the 1.0-GPH fires and seemed to be affected by the fire size as much as by the air density, since one of these was the lower airflow atmospheric blower test. The Pyrotector unit saw all the test fires in all simulated flight conditions.

## 5.2 False Alarm Immunity

During the baseline tests with the HTL/Graviner UV sensor, no false alarms occurred with the simulated hot engine soak or hot engine bleed duct tests, or with the aircraft strobe light. As the HTL representative had expected, however, this unit provided a fire warning any time an electric arc was struck by the arc welder. Only if the arc was pulsed so that its duration was shorter than the one second period that the units microprocessor required to indicate a fire, could the false alarm could be prevented.

The Kidde Company system provided no false fire warnings during its second test period. Recalling that increased sensitivity increases the probability of false alarm unless false alarm sources are actively inhibited by the detection device, it was speculated, based on previous test results, that the Kidde unit may not have been sensitive enough to observe the false alarm sources.

The SBRC system was also relatively free of false fire warnings, although its most sensitive (number 3) detector unit responded to the aircraft strobe unit any time the red lens was installed. Since the SBRC system was insensitive to all of the smaller test fires, it can be speculated that, as with the Kidde Company system, the SBRC unit may not have been sensitive enough to observe the false alarm sources.

## 6.0 CONCLUSIONS AND RECOMMENDATIONS

### 6.1 Conclusions

The AENFTS facility provided a time and cost effective environment for the evaluation of optical fire sensors in an environment representative of a typical aircraft engine compartment. The facility allowed direct comparison of the performance of dissimilar systems. Simulation of ram pressure in the test section was found to be particularly valuable. The following conclusions were reached.

1. Despite initial concern about detector system saturation, no situations were found where the larger, 31.2 GPH JP-4 fires were more difficult to sense than the smaller, 1.0-GPH JP-4 fires. Hence the use of only the smaller fires in the ongoing testing at the FAA/TC should not compromise that program.

2. The Pyrotector sensor was more sensitive to small JP-4 test fires than the baseline HTL/Graviner system in simulated altitude tests with the engine compartment at ambient pressure. The Armtec sensor was more sensitive to small fires than the baseline sensor for test simulating high (20 to 24 psia) engine compartment pressure due to ram pressure effects. Although the highest simulated ram air pressures are much higher than those in current aircraft, sensor response at high pressure may be of interest for future aircraft. Both the Pyrotector and Armtec systems were immune to all simulated false alarm sources. As mentioned previously, the HTL/Graviner sensor was immune to all false alarm signals except arc welding, which is a very unlikely source when the sensor is active.

3. The use of UV sensors, both in the case of the HTL/Graviner baseline sensor which employed UV detectors only, and the Armtec sensor which employed one UV detector in combination with two IR detectors, did not seem to provide greater sensitivity than a combination of IR sensors. Simulated engine compartment ram air pressures seemed to compromise the performance of both systems. Reliance on UV sensors seemed to degrade those systems' immunity to the simulated false alarm emissions.

4. The possibility of small fires being sufficiently far from the existing continuous element detection systems to be undetected is enough to conclude that the baseline UV, Pyrotector and Armtec systems would have sensitivity advantages over current Air Force engine compartment fire detection systems. False alarm immunity of the Pyrotector and Armtec systems was also found to be acceptable.

## 6.2 Recommendations

The AENFTS results indicate that current problems with continuous element detection systems in aircraft engine compartments could be largely eliminated by replacing those systems with optical sensor based systems. Prior to such a change on a major scale, however, other related problems need to be addressed:

1. The proximity of the sensor to the test fire was fixed in the AENFTS testing, and known in advance by the vendors. Testing of these same optical sensors is currently underway in the FAA/TC's F-111 test article at Atlantic City. The vendor's will not have had advance information on the location of the test fires within the engine compartment and will need to provide enough sensors appropriately positioned to detect a relatively small fire in any location within the engine compartment. While those tests will not include altitude and ram pressure simulation, they will provide a more severe evaluation of the complete detector systems' sensitivity to fires at ambient pressure.

2. Continuous element systems are capable of sensing overheat conditions and hot engine bleed leakage in the engine compartment whereas the optical sensors evaluated in this program probably would not. An improved engine compartment fire detection system may require optical sensors to provide fire warning in combination with a continuous element system, perhaps smaller than current systems, in areas where overheat and bleed air duct leakage are potential problems. A system which could sense both threats should be developed and evaluated before present continuous element systems could be eliminated.

3. Long term reliability, compatibility and durability of any detection system must be established prior to aircraft installation. Although the HTL/Graviner system has been used in an F-111 airplane since 1980 (see Section 3.2.1), much of the information relating to reliability was not recorded. HTL concluded (Appendix A) that, except for the optical test emitter, the overall system reliability was excellent, especially considering that no system maintenance was performed since 1981. Excluding the test emitter, HTL concluded that their system has demonstrated its ability to operate in a satisfactory manner in an aircraft engine compartment environment.

4. Testing of optical fire detection systems at FAA/TC should be completed. Detection system compatibility with environmental conditions, such as vibration, sustained high temperature (500°F) operation, and shock, as well as sensitivity to additional false alarm sources should be demonstrated for any candidate system. Since the HTL/Graviner system has been subjected to these kinds of tests, this system could again serve as a baseline. The information obtained, when used in conjunction with the test results contained in this document, should allow selection of one or more candidate systems for further evaluation.

5. The results of the ongoing reliability and false alarm evaluation of HTL/Graviner system currently installed in flight test F-111 should be monitored. Flight and maintenance crews should be informed of importance of the testing, and of adequate record keeping. The perfect record of the HTL/Graviner sensors for false alarm immunity should be emphasized as an important reason for continuing study of optical detection.

6. Consider a similar flight test evaluation program of a more advanced optical detection system. This could be performed on the same flight test F-111 by replacing either the A side, or the B side of the HTL/Graviner UV system with the system selected (when and if the criteria described in Items 3 and 4 is addressed and met)."

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## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AENFTS | aircraft engine nacelle fire test simulator |
| BIT | Built-In Test |
| CWU | crew warning unit |
| CCU | computer control unit |
| FAA/TC | Federal Aviation Administration/Technical Center |
| GPH | gallons per hour |
| IR | infrared |
| psia | pounds per square inch, absolute |
| UV | ultraviolet |

APPENDIX A. TCH:6-53

## OPERATIONAL STATUS OF SM-ALC's UVAFDS

Dates of visit: 7-8 October 1986

Location: Sacramento Air Logistics Center (SM-ALC)
McClellan AFB, CA

Purpose of visit:

(1) To assess the operational status of the Ultraviolet Aircraft Fire Detection System (UVAFDS) on the SM-ALC test aricraft FB-111A, S/N 67-159.

(2) To determine the effects of over five years of service on an optical fire detection system in an aircraft engine nacelle environment.

(3) To present UVAFDS capabilities for detecting discrete fire events, such as combustor can burn-throughs, to A-10 program office personnel.

Participants:

| | | |
|---|---|---|
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UVAFDS System Description:

Two versions of the microprocessor-coupled Ultraviolet Aircraft Fire Detection System (UVAFDS) were developed under USAF Contract F33615-77-C-2029. One version, System A, uses dual head sensors (i.e., two UV detectors mounted onto one housing) with essentially complete subsystem redundancy. Redundancy is defined as the duplication of a component or subsystem so that if the primary component fails, the secondary component is still capable of providing the desired function. System A operates as two complete and separate subsystems. It utilizes two microprocessors and two control/test electronics assemblies housed into a single computer control unit (CCU) assembly. This system is designed such that the two channels are each independently fed signals from one half of a fire sensor head (i.e., one detector head of the dual head sensor) and electronically processed through one of the microprocessors. The second channel is then fed signals from the other detector on the sensing head and similarly processed through the second microprocessor. Both channels must identify a fire warning before an indication is sent to the crew warning unit (CWU). This is termed "AND" logic.

The design of the system is such that no single failure of any part affects the fire detection capability of the system, and hence, no CWU indication of a fault is indicated (even though it is acknowledged and stored internally and later indicated when interrogated by the ground support equipment).

If for some reason one entire channel of this two channel system fails, the system recognizes this and ignores the output from the faulty channel. The remaining channel will then solely operate its half of the two headed sensors and continue to provide complete engine detection coverage. Similarly, if the fault is isolated to a single UV detector (i.e., one half of a dual head sensor), the controlling microprocessor would ignore this detector's output and the decision of whether a fire is present would be made by the other half of the sensing head.

The technique to determine if a part or component is faulty is implemented by an automatic test feature. Each detector head has a ultraviolet test emitter which excites the UV detector every 15 seconds, and a series of tests are performed through each of the microprocessors. These tests include testing the UV detector, its output signal path, the internal microprocessor program, and the opposite microprocessor's signaling and processing ability. If for some reason some portion of the system does not operate, it is shut down and the system reconfigures to ignore the faulted system's output.

System B, the other version of UVAFDS, uses single head sensors (i.e., one UV detector mounted onto one housing) and has limited redundancy features. It operates through a single channel through a single microprocessor. Like System A, it has both manual and automatic test features with the automatic test also being capable of informing its microprocessor of a faulty sensor head, hence, ignoring its output.

One feature that both Systems A and B use is adjacency. Adjacency is defined as two sensors viewing the same area/volume. Figure 1 illustrates UVAFDS adjacency design and the location of each of the sensor housings. As can be seen, sensors one and two view one hazard zone, two and three view a second hazard zone, and sensors four and

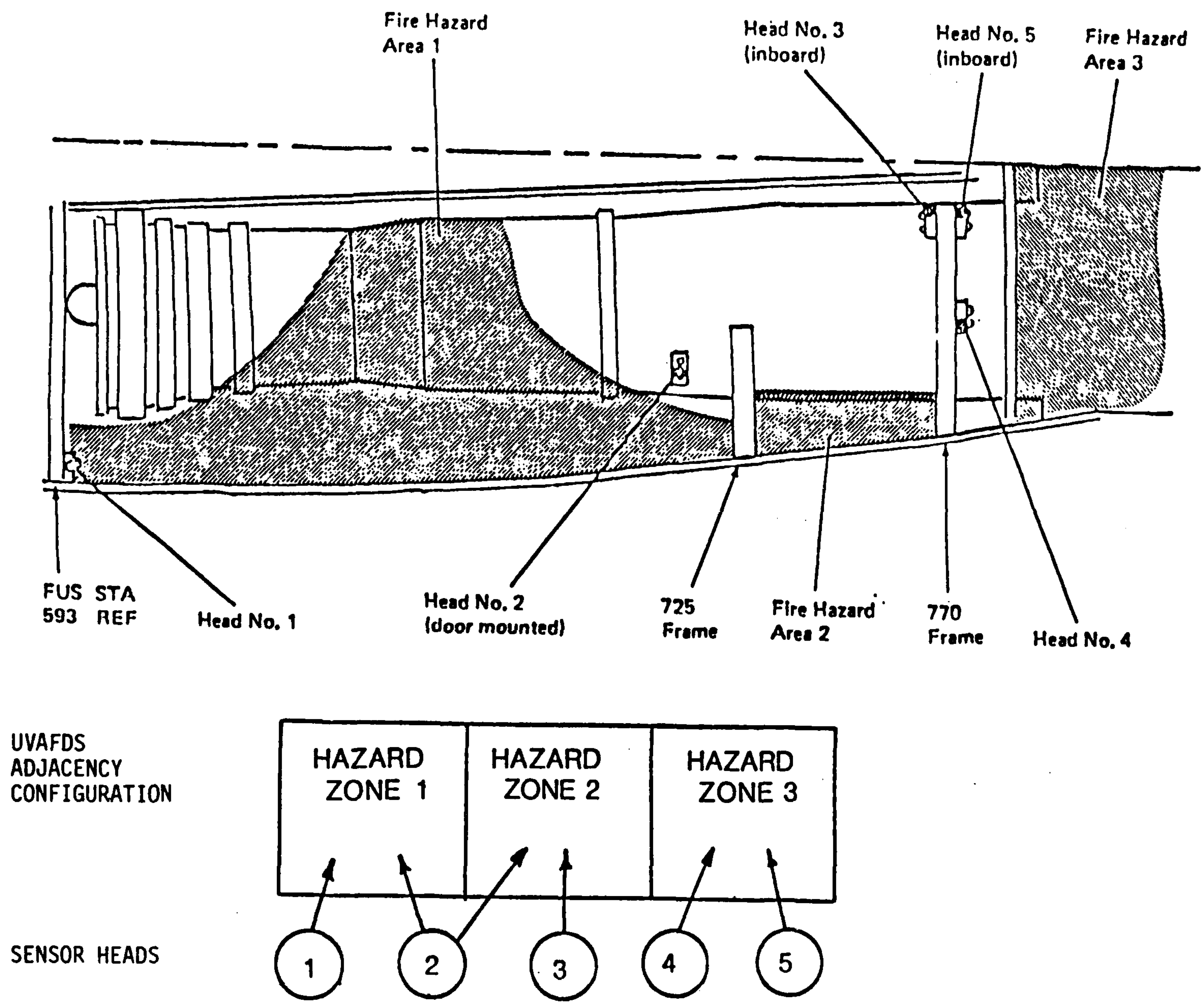


FIGURE 1. SENSOR HEAD LOCATIONS AND ADJACENCY CONFIGURATION.

five view a third hazard zone. This means that System A has four UV detectors viewing each hazard zone area, whereas System B only has two. Thus, System A can lose up to three of its four detectors without losing hazard zone coverage. System B, however, can only lose one detector and still provide hazard zone coverage. If hazard zone coverage is lost, a fault lamp is illuminated on the cockpit display (CWU). For example, in Hazard Zone 1 System A has head 1 (with UV detectors X1 and Y1) and head 2 (with detectors X2 and Y2) providing detection coverage. Any fire signals from X1 and Y1, or X1 and Y2, or X2 and Y1, or X2 and Y2 would illuminate a fire lamp on the CWU. If detector X1 was damaged, the system would ignore X1's output and wait for fire signal inputs from either Y1 and X2 or X2 and Y2. If detector Y1 is nonoperational, the system reconfigures to X2 and Y2 only. If the Y2 detector fails, then the system reconfigures so that the output from only detector X2 is capable of triggering a fire warning. Finally, if X2 fails, the fault lamp is illuminated on the CWU.

System B's adjacency operates similarly but is limited to single detector reconfiguration technique. For example, under normal operating conditions, the system will send a fire warning if a fire output is received from either detectors X1 or X2 on sensing heads 1 and 2, respectively. If either X1 or X2 detector is faulty, the remaining detector continues to provide zonal coverage. If it then fails, a fault indication will appear on the CWU.

Both System A and B use one second response times to respond to a fire so as to minimize false warnings due to transient radiation sources, such as lightning. Also, system component operational status is retained in the respective computer control unit (CCU), so that if maintenance is necessary the location of the faulty "line replacable unit" can be identified through the ground support equipment (GSE).

More detailed information about the design and operating features of both System A and B versions of UVAFDS can be found in the USAF technical report entitled, "Advanced Ultra-Violet (UV) Aircraft Fire Detection System, Volumes I, II, and III," AFWAL-TR-82-2062.

Findings:

Ron Hair, the line crew chief responsible for the maintenance of the F-111 test aircraft (FB-111A, S/N 67-159) which UVAFDS was installed upon, reported that no maintenance was performed on either version (System A or B) of UVAFDS since approximately 1983. It was understood that this was the time frame when the first signs of UVAFDS malfunction was first observed (i.e., a fault light appeared on the CWU), and Mr. Hair deemed maintenance was required. It was also the HTL representatives' impression that little or no maintenance was performed (such as, cleaning sensor heads, interrogating system operation through the GSE, etc.) on UVAFDS since 1981 after the General Dynamics/HTL/Graviner contract was completed.

Upon initial inspection of the FB-111A and UVAFDS, it was found that the right engine fault light was illuminated on the CWU. This is the engine side which has System B version of UVAFDS installed. The left engine UVAFDS system (System A) indicated that it was still operational when a manual self check was initiated through the CWU (NOTE - the CWU-initiated self-check only verifies that complete engine fire hazard zone coverage is present but does not identify if any sensor heads or their respective detectors are faulty).

Upon interrogation of the left engine UVAFDS (System A) with the GSE, it was found that Sensor 1 (detectors 1 and 2), half of sensor 2 (detector 1), half of sensor 4 (detector 1), and sensor 5 (detectors 1 and 2) were "nonoperational." The GSE interrogation method excites each detector's test emitter for ten seconds so that detector can verify that it can "see" a radiation source (NOTE - System A has five sensor housings each with two UV detectors per housing, hence ten UV test emitters). After reviewing the HTL records, it was discovered that sensor 5 was disconnected in 1981 (for reasons which will be discussed later). The fact that the other four detectors were shut-down indicated that either these UV detectors were faulty; or these UV detectors had sufficient contaminant build-up to obscure their field-of-view; or their test emitters had sufficient contaminant build-up to reduce their radiation emission properties making the CCU think that the detector heads had faulted; or the test emitters were faulty (again making the CCU think the detectors had faulted). To identify which of the above was the actual case, a UV emitting wand was placed near each sensor housing during a GSE interrogation (i.e., when the test emitter was supposed to be activated), and each detector's response was again recorded. It was confirmed that four of the ten test emitters had failed. It was also verified that one UV detector (sensor 1, detector 1) had faulted. Table 1 summarizes the findings.

The reason that sensor 5 was disconnected in 1981 was that due to its orientation in the engine nacelle it was capable of observing the engine afterburner plume and therefore responded. Sensor 4, due to its similar location, also responded to the afterburner plume. However, it was successfully partially masked with black paint to avoid afterburner plume detection while still providing fire zone coverage. In an effort to minimize costs and maintenance, the Air Force/General Dynamics opted to disconnect sensor 5 on both engines rather than remove the engines and mask them.

Although so many sensors/detectors were faulty (or the CCU thought they were faulty based on its automatic self test which utilizes the test emitter), the fault light on the CWU was not activated. The reason is that the left engine still had complete fire

detection coverage in its hazard zones. Head 2/side 2 provided coverage in Hazard Zone 1 (See Figure 1). Head 3 (both detector sides) and head 2/side 2 provided detection coverage in Hazard Zone 2, and head 4/side 2 provided coverage in Hazard Zone 3.

The right engine was next inspected. According to the GSE interrogation, all five of the System B sensing heads had faulted (NOTE - a fault light should appear on the CWU when one or more hazard zones has no fire detection coverage). Apparently, sometime in 1983 one of the hazard zones lost all of its coverage (probably, Hazard Zone 3 since System B's sensor 5 was disconnected leaving sensor 4 solely covering this hazard zone).

When the UV emitting wand was used as the UV emission source during the GSE interrogation, it was found that four of the test emitters and one of the UV sensing heads were inoperative. Table 2 summarizes the findings.

Of the UVAFDS fire sensors which could be visually inspected (sensors 1,2, and 4 of both engines), all appeared relatively clean (with respect to contaminate build-up) except for the two number four sensors. There appeared to be a large amount of "sooty-looking" particulate matter on each of these two sensors. It was thought at first that this was the reason why System B's sensor 4 (single detector) was not responding to the UV wand. However, after cleaning its detector's glass window, it still did not respond to the UV wand emission source. Furthermore, some of the "sooty" appearance was actually black paint on the bulb's glass envelope. As mentioned earlier, black paint was used to partially mask the two sensor 4's to eliminate response to the afterburner flame. Nevertheless, contamination build-up on optical sensing heads does not appear to be a problem based on the fact that one of System A's two detectors on Sensor 4 passed its automatic self-check, and both detectors responded to the UV wand (System A's sensor 4 was not and has not been cleaned off).

Several of the CWU light bulbs were also found inoperative (NOTE - there are four light bulbs per warning indicator in the CWU). The rechargable batteries used for the CCU's memory retention were also depleted, as were the GSE's rechargable batteries.

TABLE 1

Operational Status of FB-111A, S/N 67-159 Left Engine

UVAFDS System A

| Sensor | Detector | Detector Status | Emitter Status | Status of Each Side of Sensor |
|---|---|---|---|---|
| Head 1 | Side 1 | Faulty | Faulty | Nonoperational |
| | Side 2 | OK | Faulty | Nonoperational |
| Head 2 | Side 1 | OK | Faulty | Nonoperational |
| | Side 2 | OK | OK | Operational |
| Head 3 | Side 1 | OK | OK | Operational |
| | Side 2 | OK | OK | Operational |
| Head 4 | Side 1 | OK | Faulty | Nonoperational |
| | Side 2 | OK | OK | Operational |
| Head 5 | Side 1 | ? | ? | Disconnected |
| | Side 2 | ? | ? | Disconnected |

TABLE 2

Operational Status of FB-111A, S/N 67-159 Right Engine

UVAFDS System B

| Sensor/Detector | Detector Status | Emitter Status | Sensor Status |
|---|---|---|---|
| Head 1 | OK | Faulty | Nonoperational |
| Head 2 | OK | Faulty | Nonoperational |
| Head 3 | OK | Faulty | Nonoperational |
| Head 4 | Faulty | Faulty | Nonoperational |
| Head 5 | ? | ? | Disconnected |

Conclusions Based on Findings:

After inspection of the UVAFDS (Systems A and B) on FB-111A, S/N 67-159, it was found that the left engine still had fire detection coverage of its fire hazard areas, but the right engine had lost all of its detection coverage. Of the total 15 detector/test emitter combinations (a total of 10 fire sensors), it was confirmed that two UV detectors and eight test emitters were faulty. Three UV detectors with their corresponding test emitters were disconnected (i.e., sensor 5 of both engines). Although only two UV detectors were confirmed nonoperational, the fact that at least eight test emitters were nonoperational causes their corresponding detector output to be ignored in the CCU (even if the UV detector is operational). Therefore, of the total 15 detector outputs which were to be processed in the CCU, 11 detector outputs were disenabled (two faulty detectors, six additional detectors which were operational but had faulty emitters, plus the three disconnected detectors); see Tables 1 and 2.

The test emitters were integrated into UVAFDS to enhance system reliability. They are energized during manual self-tests initiated from the CWU and are automatically energized every 15 seconds anytime UVAFDS has power. Based on the findings from this investigation, it appears that instead of enhancing system reliability, the test emitters actually inhibit reliability. It was discovered by Graviner (approximately three years after UVAFDS was constructed) that these test emitters were extremely fragile and had a low MTBF associated with them. When a second generation of UVAFDS is constructed, this shortcoming will be eliminated (e.g., by replacing the current test emitters with ones that have MTBF exceeding the UV detectors or by eliminating the test emitters completely from the UVAFDS design).

While the right engine with System B had lost all of its detection coverage (primarily due to faulty test emitters and the disconnection of sensor 5), the left engine with System A was still providing total fire zone coverage (even though the CCU shut-down four detectors and two sensor 5 detectors were disconnected). The reason System A is able to continue providing coverage is because of the adjacency and redundancy features designed into UVAFDS. Detector 2 of sensor 2 was monitoring Fire Zone 1 (detector 1 of sensor 2 and both detectors of sensor 1 were shut-down or nonoperational). Detector 2 of sensor 2 and both detectors of sensor 3 monitored Fire Zone 2, and detector 2 of sensor 4 monitored Fire Zone 3 (detector 1 of sensor 4 and both detectors of sensor 5 were shut-down or disconnected). The redundancy of System A enabled the UVAFDS to reconfigure so that only four detector/emitter combinations monitored all the fire zones. This is indeed a selling point for redundancy in an aircraft system. However, it should be pointed out that if all the test emitters had been functional, both the left and right engines of the F-111 test aircraft would have had complete fire zonal coverage (assuming sensor 5's were not faulty on both System A and B). If this were the case, all sensors of system A would be operational with the exception of one half of sensor 1, and all sensors of system B would be operational except sensor 4. Sensor 5 of System B would continue to provide coverage for the right engine's Fire Zone 3 in this case. This scenario clearly indicates that adjacency features are more advantageous than redundancy features if reliable components are used in the system design.

While it is unfortunate that HTL/Graviner chose such an unreliable component (test emitter) to test the integrity of a basically reliable system and gave this unreliable component the "authority" to shut down an operational component (UV detector), it is a design problem which has been resolved and will be corrected in the next generation UVAFDS.

With the exception of this particular problem, UVAFDS overall condition (considering it had not received any maintenance attention for up to five years) was impressive.

HTL plans on continuing to pursue approaches for the next generation UVAFDS which is independent of battery power (for CCU memory retention). The infrequent use of the SM-ALC's F-111 appears conducive to depleting their CCU batteries. Also, HTL will continue to seek longer lasting CWU light bulbs (as will the rest of the world).

Recommended Action:

Since removal of UVAFDS from FB-111A (S/N 67-159) may upset the weight and balance of that aircraft, it is recommended that UVAFDS remain onboard. It is furthermore recommended that it be brought back up so that it is completely operational. The following is proposed as an interim plan to accomplish this:

(1) Determine UVAFDS operational status; complete

(2) Report operational status to USAF; pending release of this report

(3) Ship WPAFB UVAFDS system to HTL; complete

(4) Identify suitable components (from WPAFB's UVAFDS) for later integration into SM-ALC's F-111 UVAFDS; 31 Oct. 86.

(5) HTL report status of WPAFB's UVAFDS to USAF; 14 Nov 86

(6) HTL return to SM-ALC with replacement components (including WPAFB supplied components, new GSE batteries, new CCU batteries, and new CWU light bulbs) and diagnostic test equipment to repair SM-ALC's UVAFDS; as soon as FB-111A (S/N 67-159) is grounded for one day.

(7) HTL report to USAF on SM-ALC's UVAFDS faults, causes, and future corrective action; two weeks after item (6) completed.

(8) HTL return all un-used UVAFDS hardware to WPAFB; two weeks after item (6) completed

(9) HTL and WPAFB remain in contact with SM-ALC on a quarterly basis for any required maintenance actions.

While this interim plan is being pursued, HTL plans on investigating the possibilities of replacing the UVAFDS test emitters with new-and-improved emitters and/or constructing new sensing heads.

Please forward any comments or questions to the undersigned.

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29 October, 1986
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## APPENDIX B.

## AEN DATA REDUCTION EQUATIONS

The following three sections provide the equations which will be used to calculate airflows and velocities for the eight and twenty four inch venturiis, the high pressure air supply system and for the sonic nozzles used to measure simulated bleed airflow, ejector flow and high pressure flow.

1.0 Calculation of 8 Inch Venturi Mass Flow and Velocity:

Per the Reference 7, Compressed Gas Handbook, the mass flow through a venturi meter in lbs/sec. is equal to:

$$W = Cd * A2 \sqrt{\frac{(2 * g * rho * DP)}{1 - beta^{4}}} \sqrt{\frac{r^{2/k} \left( k \right)\left( 1 - r^{(k-1)k} \right)\left(1-beta^{4}\right)}{(k-1)\ (1-r)\left(1-r^{2/k} * beta^{4}\right)}}$$

Where the first radical term is the incompressible flow equation and the second radical term is the compressibility correction, and:

W = mass flow in lbs/sec

Cd = discharge coefficient

g = gravitational constant

rho = upstream density

DP = differential pressure across venturi

beta = ratio of throat diameter to upstream pipe diameter, D2/D1

k = specific heat ratio

r = ratio of upstream to downstream pressure, P2/P1

For air (k = 1.4) this simplifies to:

$$W = .525\ Cd * D2^{2} \sqrt{\frac{rho * DP}{1 - beta^{4}}} * \sqrt{\frac{r^{1.429}\ (3.5)\left(1-r^{.2857}\right)\left(1-beta^{4}\right)}{(1 - r)\ \left(1 - r^{1.429} * beta^{4}\right)}}$$

Hence, substituting AEN parameters:

P1 = PFLIN (venturi upstream static pressure in psia)

DP = DPVN40 * .03606 (venturi differential pressure from high range transducer when differential pressure greater than 4 inches of water)

or

DP = DPVN-4 * .03606 (venturi differential pressure from low range transducer when differential pressure less than 4 inches of water)

$$RHO = \frac{P1 * 144}{(53.35) * (TBL\text{-}08 + 460)}$$

(Where TBL-08 is 8 Inch Venturi Temperature)

$$R = \frac{P1 - DP}{P1}$$

or, if R < 0.6, or R > 1.0, substitute R = 1.0

For the eight inch venturi, Cd = 0.985, D2 = 4.1768, beta = 0.4968

$$K = .525 * 0.985 * (4.1768)^{2} * \sqrt{3.5} = 16.877842$$

$$WBL\text{-}08 = K * \sqrt{\frac{RHO * DP * ( R^{1.429} ) * ( 1 - R^{0.2857} )}{( 1 - R ) * [ 1 - ( R^{1.429} ) * 0.0609153]}}$$

This is the test section mass flow in lbs/second.

$$VNAC\text{-}8 = \frac{(0.152 * WBL\text{-}08) * (TNACIN + 460)}{PNCOUT}$$

: Clean Test Section Velocity in FT/SEC.

Where TNACIN is the test section inlet temperature in degrees F. and PNCOUT is the in test section pressure in psia.

2.0 Calculation of 24 Inch Venturi Mass Flow and Velocity:

Using the same equation as for the eight inch venturi, but with:

Cd = 0.9895, D2 = 10.158, beta = 0.4277

$$K = 0.525 * 0.98975 * (10.158)^2 * \sqrt{3.5} = 100.307926$$

P1 = PBLOUT (venturi upstream static pressure in psia)

DP = DPVENT * .03606 (venturi differential pressure)

If DP < 0, DP = 0

$$RHO1 = \frac{P1 * 144}{(53.35) * (TBL\text{-}24 + 460)}$$ (Where TBL-24 is 24 Inch Venturi Temperature)

$$R = \frac{P1 - DP}{P1}$$ or, if R < 0.6, or R > 1.0, substitute R = 1.0

K = 100.307926

$$WBL\text{-}24 = K * \sqrt{\frac{RHO1 * DP * (R^{1.429}) * (1 - R^{0.2857})}{(1 - R) * [1 - (R^{1.429}) * 0.0334624]}}$$

This is the test section mass flow in lbs/second.

$$VNAC24 = \frac{(0.152 * WBL\text{-}24) * (TNACIN + 460)}{PNCOUT}$$

This is the clean test section velocity in ft/second where TNACIN is the test section inlet temperature in degrees F. and PNCOUT is the test section temperature in psia.

## 3.0 CALCULATION OF AIRFLOW FOR SONIC NOZZLES

The manufacturer of the sonic nozzles installed in the AEN, Flow Measurement Systems, Inc., provides the following equation for calculation of sonic nozzle airflow in Reference 8:

$$W = \frac{P^{o} * A * C^{*} * C_{d}}{\sqrt{T + 460}}$$

Where:

$W$ = Airflow in lbs/second

$P^{o}$ = Nozzle inlet stagnation pressure

$C^{*}$ = Critical flow function for air

$A$ = Nozzle throat area in square inches

$C_{d}$ = Nozzle discharge coefficient

$T$ = Nozzle inlet temperature, degrees Rankine

The Reference 8 memo further states that the ratio of nozzle stagnation to measured static pressure is a function of the approach Mach number and hence of the ratio of nozzle throat to pipe diameter. Thus it is a constant for each nozzle. The Reference 8 memo provides diameters, areas, and stagnation to static pressure ratios for the original 3 nozzles installed in the AEN. Using the same methods, the 4th nozzle, the bleed air heater system nozzle has been added to these:

| Nozzle No. | Location | Diameter (inches) | Area ($in^2$) | $P^{o}/P$ |
|---|---|---|---|---|
| 1 | Hi flow/Hi pressure | .9264 | .6740 | 1.0019 |
| 2 | Lo flow/Hi pressure | .3712 | .1082 | 1.0003 |
| 3 | Ejector | .8075 | .5121 | 1.0011 |
| 4 | Bleed air heater | .2964 | .0690 | 1.0001 |

$C^{*}$ is obtained from NASA TN D-2565 and is relatively constant within the range of temperatures and pressures anticipated. It is equal to .5351 at 520° and 200 psia.

$C_d$ is calculated based on Reynolds number and is obtained using:

$$N_R = (4 * W)/( 3.14159 * d * mu)$$

and

$$C_d = .99738 - \frac{3.3058}{\sqrt{N_R}}$$

In the range of Reynolds numbers anticipated, $C_d$ varies only from .993 to .996, however, so a constant .995 is employed in all these calculations.

Hence:

$$WHIFLO = \frac{1.0019\ (.6740)\ (.5351)\ (.995)\ (\ PHIFLO\ )}{\sqrt{THIFLO + 460}} = \frac{.3595\ (\ PHIFLO\ )}{\sqrt{THIFLO + 460}}$$

$$WLOFLO = \frac{1.0003\ (.1082)\ (.5351)\ (.995)\ (\ PLOFLO\ )}{\sqrt{TLOFLO + 460}} = \frac{.0576\ (\ PLOFLO\ )}{\sqrt{TLOFLO + 460}}$$

Since no temperature is measured at the ejector and the ejector airflow is not employed in subsequent data reduction, being only an indicator in setting test section pressure, a constant temperature of 60° F. is assumed.

$$WEJFLO = \frac{1.0011\ (.5121)\ (.5351)\ (.995)\ (\ PEJFLO\ )}{\sqrt{60 + 460}} = .001197\ (\ PEJFLO\ )$$

$$WBLHTR = \frac{1.0001\ (.0690)\ (.5351)\ (.995)\ (\ PBHNOI\ )}{\sqrt{TBHNOI + 460}} = \frac{.03674\ (\ PBHNOI\ )}{\sqrt{TBHNOI + 460}}$$